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Methods of Preparing Horizontal Construction Joints in Mass Concrete

by Billy D. Neeley, Toy S. Poole

Prepared for Headquarters, U.S. Army Corps of Engineers

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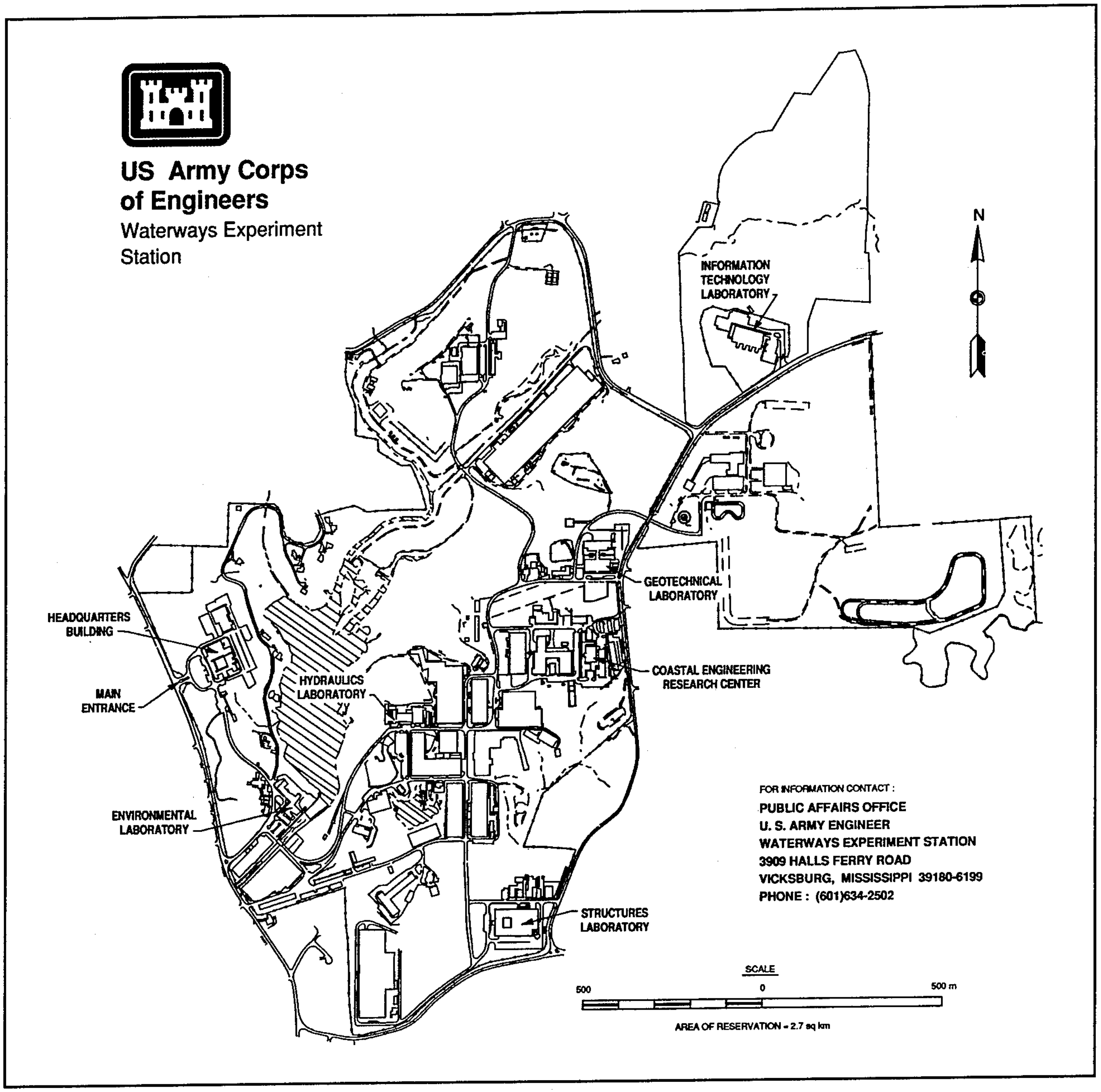

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Contents

Preface

The investigation described in this report was conducted by the Concrete Technology Division (CTD), Structures Laboratory (SL), U.S. Army Engineer Waterways Experiment Station (WES). The work was sponsored by Headquarters, U.S. Army Corps of Engineers, as a part of Civil Works Investigation Studies Work Unit 32767, "Horizontal Construction Joint Treatment in Mass Concrete."

The study was conducted under the general supervision of Messrs. Bryant Mather, Director, SL, and James T. Ballard, Assistant Director, SL, and Dr. Tony C. Liu, Acting Chief, CTD. Direct supervision was provided by Mr. Steven A. Ragan, Chief, Engineering Mechanics Branch (EMB), CTD. Mr. Billy D. Neeley was the Principal Investigator and coauthored this report with Dr. Toy S. Poole, Engineering Sciences Branch, CTD, who performed the statistical analysis of the test data. Messrs. Michael Lloyd, Jimmy Hall, Cliff Gill, and Michael Hedrick, EMB, CTD, assisted in preparing and testing the concrete specimens.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

1 Introduction

Background

Under ideal conditions, any mass concrete structure should be monolithic. However, mass concrete structures usually contain horizontal construction joints because it is impractical to place such a large volume of concrete without lengthy interruptions. These joints must be capable of transmitting stress combinations, including tension, compression, and horizontal shear, from one part of the concrete structure to another. As a minimum, a horizontal construction joint must have bond, tensile, and shear strengths greater than the stresses to which it will be subjected. Ideally, the strength of the joint should be equal to that of the surrounding concrete.

Planes of weakness can result if horizontal construction joints are not prepared properly during construction. Structural weakness, leakage, and subsequent deterioration can result from a poorly prepared horizontal construction joint. The quality of a horizontal construction joint in mass concrete depends on both the quality of the concrete, both above and below the joint, and the preparation of the joint surface.

Experience has shown that the lower surface of a joint plane must be cleaned thoroughly prior to placement of fresh concrete to ensure good bond strength and watertightness of the two layers. Various methods of cleaning the lower surface of a joint plane have been used. Civil Works Guide Specification CWGS-03305, "Mass Concrete" (Headquarters, Department of the Army 1992), has provisions for cleaning by air-water cutting, high-pressure water jet, or wet sandblasting. It states that all laitance and inferior concrete should be removed so that clean, well-bonded coarse aggregate particles are exposed over the lift surface. However, the coarse aggregate particles should not be undercut. Use of a surface retarder is permitted to extend the period of time during which air-water cutting is effective. CWGS-03305 also states that the surface of a construction joint should be kept continuously wet for the first 12 hr of the 24-hr period prior to placing the fresh concrete, except that the surface shall be damp with no free water at the time of placement.

Between 1959 and 1973, four technical reports were published by the U.S. Army Engineer Waterways Experiment Station (WES) describing the results of an investigation of methods of preparing horizontal construction joints (Tynes 1959; Tynes 1963; McDonald and Smith 1966; Tynes and McCleese 1973). These investigations generally concluded that (a) wet sandblasting, air-water cutting, and high-pressure water jetting were effective methods of cleaning a joint surface, (b) application of mortar to a joint surface did not improve the integrity of the joint, and (c) a stronger and more impermeable joint will result if the hardened concrete surface is dry when the fresh concrete is placed. More recently, Pacelli, Andriolo, and Sarkaria (1993) presented case histories of investigations regarding the performance of construction joints in five large concrete dams. Test results indicating the bond and shear strengths of new concrete placed on the cleaned and roughened surface of existing concrete were presented. Their investigations generally concluded that (a) high-pressure water-jetting and air-water cutting were as effective as wet sandblasting for cleaning a joint surface, (b) properly prepared construction joints had shear and tensile strengths equal to at least 85 percent of that of the intact concrete, (c) roughness of the joint surface did not have a significant influence on the strength of the joint, (d) application of mortar to a joint improved the joint strength only if the joint surface was not properly cleaned, and (e) the permeability of a properly prepared joint was essentially the same as that of the intact concrete.

The results presented in the four WES technical reports were used as guidance in preparing the current issue of CWGS-03305 (Headquarters, Department of the Army 1992). However, there are some differences in concrete mixtures and typical placement procedures used today compared to those used 25 years ago. For example, at the time of the earlier investigations, most mass concrete was lean, high water-cement ratio (w/c) concrete using 150-mm nominal maximum size aggregate (NMSA). Today, many mass concrete structures are more heavily reinforced and are constructed using 75-mm or even 37.5-mm NMSA concrete having lower w/c. Also, at the time of the earlier investigations, most mass concrete was very low slump and placed by buckets. Today much mass concrete is of higher slump and placed by other methods such as conveyors. Also, there is some disagreement about the amount of cleaning necessary, even though CWGS-03305 provides guidance in this area. In light of the differences in typical mass construction today and that of 25 years ago, the area of proper joint preparation needed to be revisited to confirm existing guidance or, if necessary, update it.

Objectives

The objectives of this research program were as follows:

a. Confirm the joint surface moisture condition needed to produce a joint having the greatest bond strength and watertightness.

b. Confirm that cleaning by high-pressure water jetting and air-water cutting produces a good quality construction joint.

c. Determine the extent of air-water cutting required to produce a good quality construction joint.

Scope

Mass concrete monolithic models similar to those used in the earlier investigations were constructed. Variables included type and amount of joint cleanup and surface moisture condition. Properties tested were direct tensile strength of the joint, shear strength of the joint, and water permeability of the joint. A test matrix is given in Table 1. Many of the measurements were made and recorded in non-SI units and converted to SI units using conversion values in ASTM E 380 (ASTM 1992).

Table 1
Test Matrix

Block Identifier	Type of Joint Preparation	Moisture Condition of Joint
A	None	Wet continuously
B	None	Dry 24 hr before placement
C	None	Wet continuously, then dry 16 hr prior to placement, then moisten surface immediately before placement.
D	High-pressure water cutting	Wet continuously
E	High-pressure water cutting	Dry 24 hr before placement
F	High-pressure water cutting	Wet continuously, then dry 16 hr prior to placement, then moisten surface immediately before placement.
G	Air-water cutting	Wet continuously
H	Air-water cutting	Dry 24 hr before placement
I	Air-water cutting	Wet continuously, then dry 16 hr prior to placement, then moisten surface immediately before placement.
J	Air-water cutting, more depth	Wet continuously
K	Air-water cutting, more depth	Dry 24 hr before placement
L	Air-water cutting, more depth	Wet continuously, then dry 16 hr prior to placement, then moisten surface immediately before placement.

2 Experimental Program

General

The materials and concrete mixtures used in this investigation were typical of those currently used in mass concrete construction. A brief description of the materials, mixtures, and test specimens is given below.

Materials and Mixture

Materials

The coarse aggregate was 75-mm nominal-maximum-size (NMS) crushed limestone. The fine aggregate was a natural river sand. The grading (American Society for Testing and Materials (ASTM) C 136) (ASTM 1992e) of each aggregate and values of absorption and specific gravity (ASTM C 127 (coarse aggregate) and C 128 (fine aggregate)) (ASTM 1992c,d) are given in Table 2.

The cement was portland cement, conforming to Type II requirements of ASTM C 150 (ASTM 1992h). The fly ash conformed to Class F requirements of ASTM C 618 (ASTM 1992m). Physical and chemical properties of the cement and fly ash are given in Tables 3 and 4, respectively.

Mixture

The concrete mixture was proportioned in accordance with American Concrete Institute (ACI) 211.1, "Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete" (ACI 1992). The mortar content for the mixture was within the range recommended by ACI 211.1 for concrete mixtures containing 75-mm NMS aggregate. The combined grading of the coarse aggregate is given in Figure 1. Forty percent of the volume of cementitious materials was fly ash. The concrete mixture proportions are given in Table 5. Tests were conducted on the fresh concrete to determine slump (ASTM C 143) (ASTM 1992g), unit weight (ASTM C 138)

Table 2
Aggregate

Sieve Size	Cumulative Percent Passing			
	Coarse Agg. (A)	Coarse Agg. (B)	Coarse Agg. (C)	Fine Agg.
75 mm	100			
50 mm	45	100		
37.5 mm	5	96		
25.0 mm		29	100	
19.0 mm		7	97	
12.5 mm		3	65	
9.5 mm		3	39	
4.75 mm		2	6	100
2.36 mm			1	80
1.18 mm				68
600 μm				57
300 μm				23
150 μm				2
Specific Gravity	2.72	2.74	2.71	2.60
Absorption, %	0.2	0.3	0.2	1.17

Table 3
Portland Cement

Property	Result	Property	Result
SiO_2, %	21.4	C_3A, %	6
Al_2O_3, %	3.4	C_3S, %	61
Fe_2O_3, %	2.4	C_2S, %	16
CaO, %	63.7	C_4AF, %	7
MgO, %	3.8	Heat of hydration, kJ/kg	305
SO_3, %	2.8	Surface area, m^2/kg	371
Loss on ignition, %	1.1	Autoclave expansion, %	0.08
Insoluble residue, %	0.06	Initial set (Gillmore), min	165
Na_2O, %	0.18	Final set (Gillmore), min	265
K_2O, %	0.74	Air content, %	9
Alkalies - total as Na_2O, %	0.67		
TiO_2, %	0.15	Compressive strength, 3 days, MPa	21.8
P_2O_5, %	0.10	Compressive strength, 7 days, MPa	28.1
		False set	88

Table 4
Fly Ash

Property	Result	Property	Result
SiO_2, %	55.6	Loss on ignition, %	4.3
Al_2O_3, %	28.8	Available alkalies, %	0.88
Fe_2O_3, %	6.2	Fineness, residue 45-μm sieve, %	12
Sum SiO_2, Al_2O_3, Fe_2O_3, %	90.7	Water requirement, %	98
MgO, %	1.0	Density, Mg/m^3	2.26
SO_3, %	0.4	Autoclave expansion, %	-0.04
Moisture content, %	0.1	Pozzolanic activity with lime, MPa	10.2
		Strength activity with cement, %	89

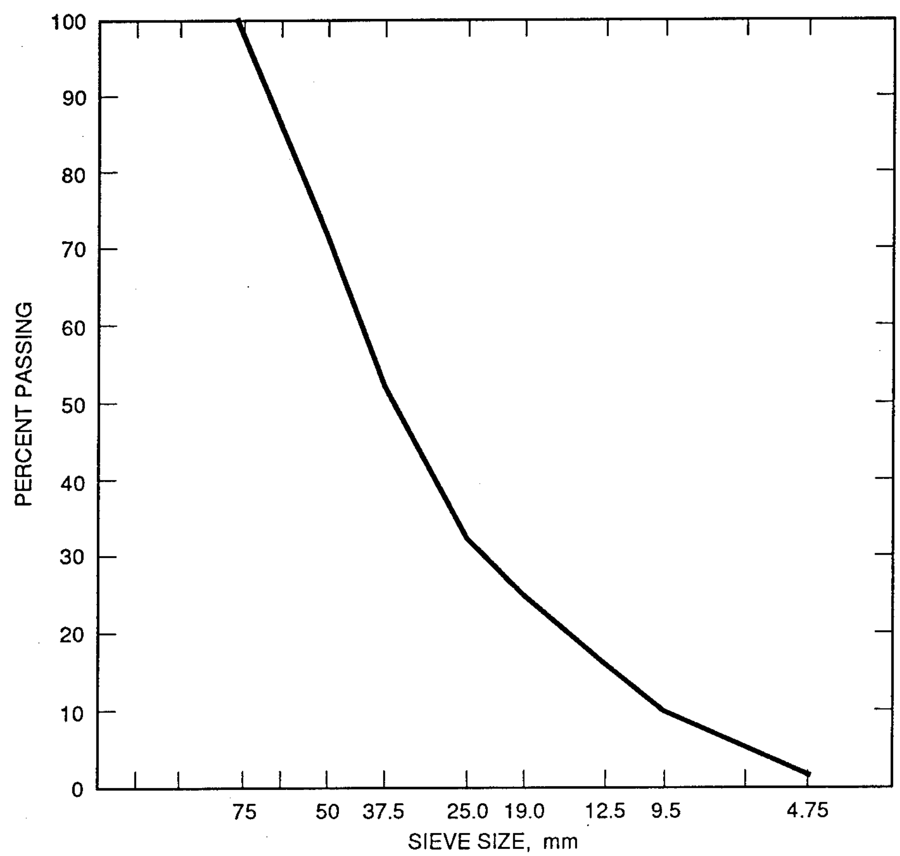

Figure 1. Combined gradings of coarse aggregate

Table 5 Concrete Mixture Proportions		
	1 cubic metre	
Material	Mass, kg	Volume, m^3
Portland cement	109	0.035
Fly ash	52	0.023
Fine aggregate	646	0.248
Coarse aggregate (A)	737	0.271
Coarse aggregate (B)	409	0.149
Coarse aggregate (C)	360	0.133
Water	100	0.100
Air-entraining admixture	0.19 litre	
Water/cement + fly ash	0.55	

(ASTM 1992f), and air content (ASTM C 231) (ASTM 1992j). Cylindrical specimens (152-mm diam by 305-mm high) were prepared according to ASTM C 192 (ASTM 1992i) and cured in a moist curing room meeting the requirements of ASTM C 511 (ASTM 1992l) until time of testing. Specimens were tested in unconfined compression at 7-, 14-, 28-, and 90-days age according to ASTM C 39 (ASTM 1992a). Results of tests on the fresh concrete and the unconfined compressive tests are given in Table 6.

Table 6
Test Results, Fresh and Hardened Concrete

Series[1]	Test Blocks	Layer	Slump mm	Air Content[2] %	Unit Weight[2] kg/m^3	Compressive Strength, MPa 7 day	14 day	28 day	90 day
1	A,B,C	bottom	40	6.9	2,300	10.4	12.6	16.6	17.3
		top	30	4.2	2,355	13.2	19.7	23.4	28.9
2	D,E,F	bottom	30	5.4	2,415	11.3	15.1	15.9	22.8
		top	30	5.7	2,380	11.5	14.3	17.2	23.7
3	G,H,I	bottom	30	4.9	2,345	9.8	12.1	16.8	23.1
		top	20	5.4	2,375	8.8	12.2	16.5	21.9
4	J,K,L	bottom	50	5.3	2,320	10.0	13.1	17.1	--[3]
		top	40	5.0	2,345	7.5	9.5	13.5	--[3]

[1] Series 1 & 2: Bottom - average of two batches
Top - average of two batches
Series 3 & 4: Bottom - average of four batches
Top - average of three batches
[2] In that portion of the concrete containing aggregate smaller than the 37.5-mm sieve.
[3] Specimens not tested due to an oversight.

Test Blocks

The twelve conditions (four joint-treatment methods and three moisture conditions) described in the experimental program were each represented by a single test block of concrete, designated A through L. The 12 conditions are described in Table 1. Each block was 1.83 m long, 0.53 m wide, and 0.75 m high. Each block was cast in two lifts. The first lift was 0.45 m deep. The surface of the fresh concrete was not finished. Curing was accomplished by covering the top surface of the concrete with wet burlap and plastic sheeting. After curing, surfaces were prepared and the second lift, containing a mortar dye for color contrast, was placed. The second lift was 0.3 m thick. Details of curing, joint preparation, and other treatments for each experimental condition are described below.

No joint cleanup

Block A (continuously wet) was cured with wet burlap and sheet plastic for 14 days, after which the covering was removed, the surface brushed with a bristle broom and vacuumed to remove loose particles, and the second lift was placed. Block B (dry) was cured with the burlap and plastic for 13 days, after which the surface was allowed to dry for 24 hr. The surface was brushed and vacuumed, and the second lift was placed. Block C (dry then rewet) was cured with burlap and sheet plastic for 13 days, after which the surface was allowed to dry for 16 hr. The surface was then remoistened, brushed and vacuumed, and the second lift was placed. Photographs of the concrete surfaces as prepared are shown in Figures A1 through A6 in Appendix A.

High-pressure water cutting

Block D (continuously wet) was cured with wet burlap and sheet plastic for 7 days, then the top surface was cleaned with a high-pressure water jet at 22 MPa. All visible laitance was removed, and coarse aggregate particles were exposed but not undercut. Curing was reapplied through 14 days, then the surface was vacuumed and the second lift placed. Block E (dry) was treated like Block D, except the second curing period was terminated after 13 days and the surface allowed to dry for 24 hr prior to placement of the second lift. Block F (dry then rewet) was treated like Block D, except the second curing period was terminated after 13 days, the surface allowed to dry for 16 hr, remoistened, and then the second lift was placed. Photographs of the concrete surfaces as prepared are shown in Figures A7 through A12 in Appendix A.

Air-water cutting

Block G (continuously wet) was cured with burlap and sheet plastic for 17 hr, then the top surface was cleaned with air-water cutting at 0.7 MPa. All visible laitance was removed, and coarse aggregate particles were exposed but not undercut. Curing was reapplied through 14 days, then the surface was vacuumed and the second lift placed. Block H (dry) was treated like Block G, except the second curing period was terminated after 13 days and the surface allowed to dry for 24 hr prior to placement of the second lift. Block I (dry terminated after 13 days, the surface allowed to dry for 16 hr, remoistened, and then the second lift was placed. Photographs of the concrete surfaces as prepared are shown in Figures A13 through A18 in Appendix A.

Air-water cutting (more depth)

Block J (continuously wet) was cured with burlap and sheet plastic for 6 hr, then the top surface was cleaned with air-water cutting at 0.7 MPa. All laitance was removed and coarse aggregate particles were exposed and slightly undercut. Curing was reapplied through 14 days, then the surface was vacuumed, and the second lift placed. Block K (dry) was treated like Block J, except the second curing period was terminated after 13 days and the surface allowed to dry for 24 hr prior to placement of the second lift. Block L (dry then rewet) was treated like Block J, except the second curing period was terminated after 13 days, the surface allowed to dry for 16 hr, remoistened, and then the second lift was placed. Photographs of the concrete surfaces as prepared are shown in Figures A19 through A24 in Appendix A.

Tests and Preparation of Test Specimens

A minimum of twelve 152-mm-diameter cores were taken from each test block using a diamond bit core barrel, according to ASTM C 42 (ASTM 1992b). Cores were cut perpendicular to the horizonal joint, completely through the test block, as shown in Figure 2. Cores were randomly selected

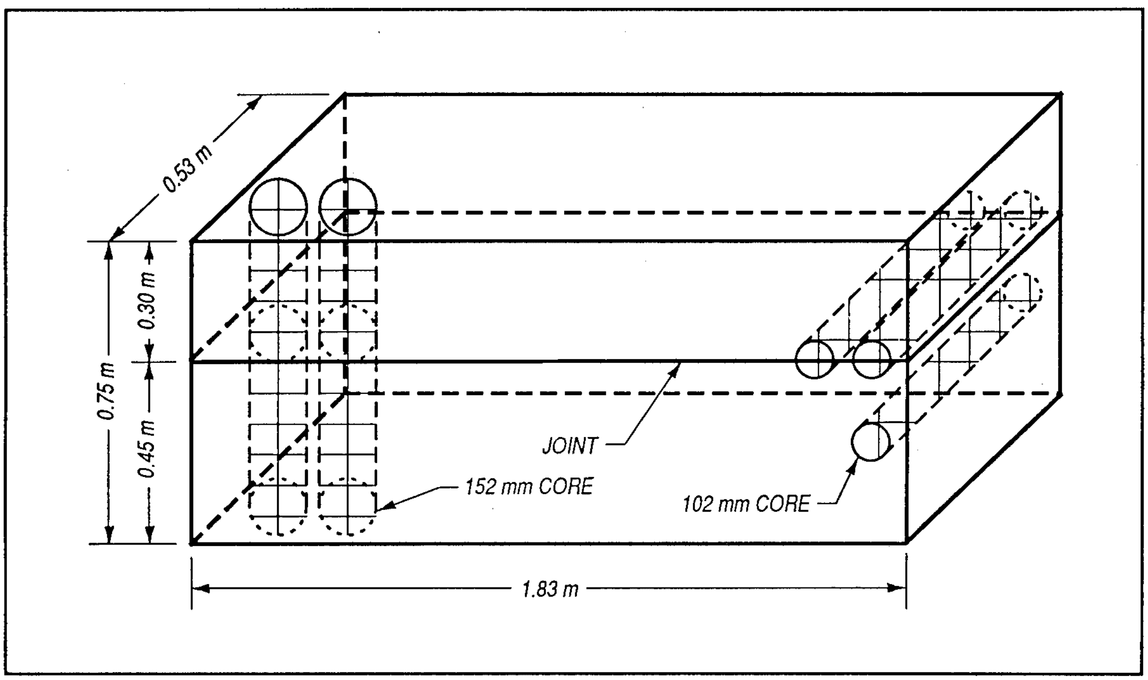

Figure 2. Test article

for direct tensile testing or shear testing. Test specimens were then cut from the cores as illustrated in Figure 3. This resulted in six intact specimens and six specimens with joints for direct-tensile strength testing according to CRD-C 164 (USAEWES 1949b), six intact specimens and six specimens with joints for shear-strength testing according to RTH-203 (USAEWES 1989), and six intact specimens for compressive-strength testing according to ASTM C 42 (ASTM 1992b). Shear strength was measured at three levels of normal loading. Nominal values of normal stress were 192, 383, and 766 kPa, although actual values were recorded. Two specimens were tested at each level of normal load to determine the maximum shear strength at failure of the joint plane. A linear regression line was calculated with normal stress as the independent variable (X) and measured shear strength as the dependent variable (Y). The Y intercept (shear at zero normal loading) was taken as the cohesion. The standard error of the intercept was used to compare results among treatment conditions. The coefficient of internal friction, ϕ, is the arctan of the slope of the regression line. The standard error of the slope was used for statistical evaluations of ϕ. After maximum shear determinations had been completed, shear testing was repeated on the broken specimens to determine the residual values of cohesion and ϕ. Residual values of cohesion and ϕ were calculated by the same linear regression procedure as for maximum shear strength.

A minimum of four 102-mm-diam cores were taken from each test block for permeability testing according to CRD-C 163 (USAEWES 1949a). These were drilled parallel to and through the joint between the first and second lifts. Two cores were similarly drilled but away from the joint. These cores are also illustrated in Figure 2. Cores were cut into 102-mm-long test specimens, resulting in six intact specimens and six specimens with joints.

Permeability is measured in units of m^2. However, in the jointed specimens it was assumed that the movement of water through the specimen occurred at the joint interface, not uniformly over the entire surface area of the core. Therefore, the length of the joint became a factor in the permeability. Since the length of the joint was not uniform in all cores, the measured permeabilities were divided by the length of the joint in the cross section of the specimen. Therefore, the results reported for jointed specimens are in units of m^2/m. These units allow comparisons to be made among different cleanup procedures and moisture conditions.

Numbers of specimens actually tested for each property differed from the number in the experimental design because some were broken during drilling or sawing. Actual numbers tested are indicated in the tabulation of results.

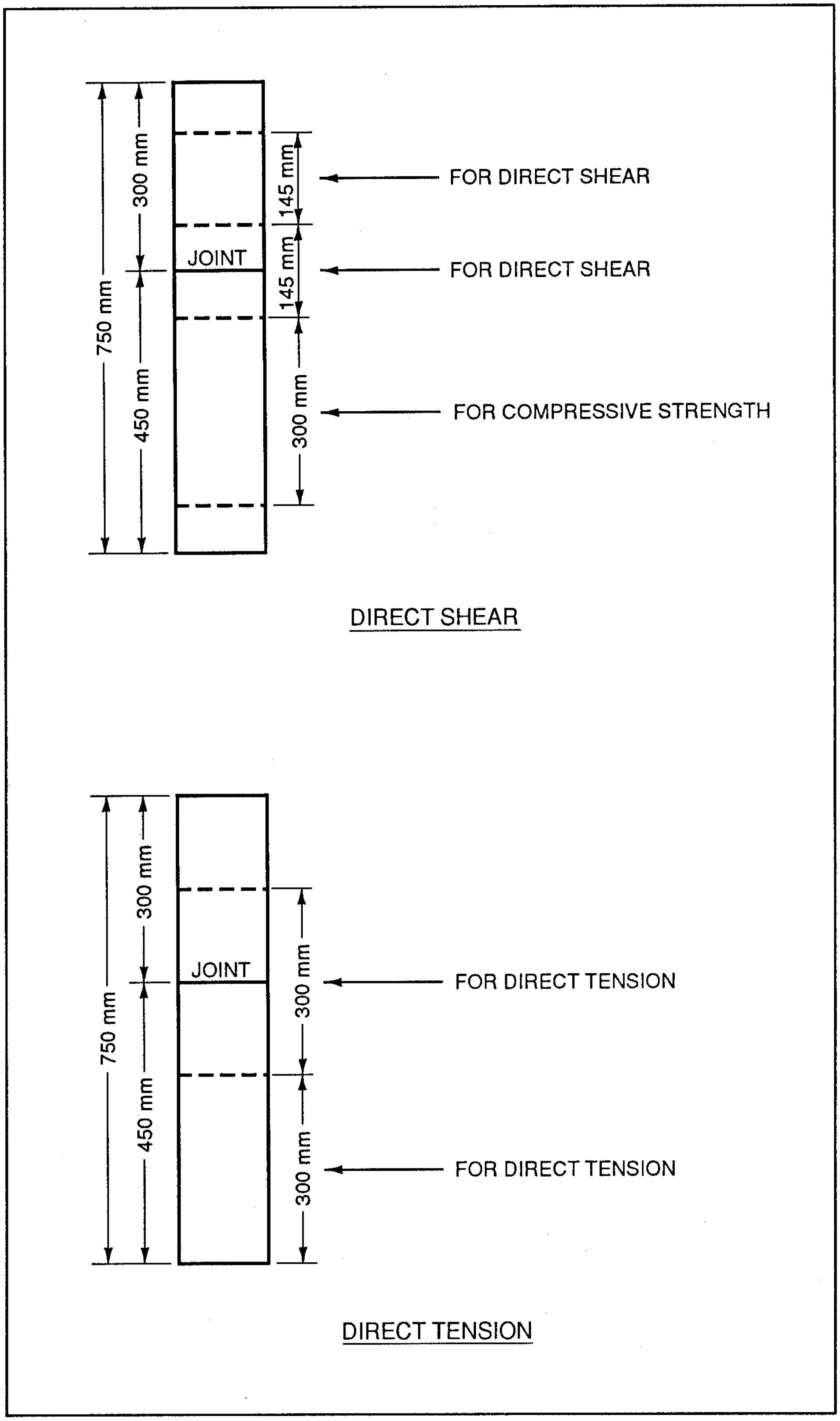

Figure 3. Preparation of cores

3 Test Results and Statistical Analysis

Direct Tensile Strength

Results of direct tensile-strength testing are presented in Table 7. Data were analyzed in a two-way analysis of variance (Appendix B), using a $P \leq 0.05$ as the decision criterion in identifying significant results. Joint preparation method and joint moisture condition are the independent treatment conditions. Comparisons among individual means were done with Duncan's Multiple Range Test. A comparison of these means is illustrated in Figure 4.

There were significant differences both among joint-treatment conditions and moisture conditions, but type of joint treatment had the largest effect on tensile strength. The high-pressure water and air-water preparation methods resulted in about the same tensile strengths, both of which were significantly higher than the air-water cutting to extra depth and the no-treatment condition. The no-treatment condition showed the lowest tensile strength.

Surfaces that were dry or dry followed by rewetting gave higher tensile strengths than continuously wet surfaces for three of the four surface treatment conditions (no treatment, high-pressure water cutting, and air-water cutting). In the case of the air-water cutting to extra depth (air-water+), the results were in reverse of the these results. The continuously wet condition resulted in significantly higher tensile strengths that the dry or dry-rewet conditions.

Tests on intact specimens contain no information about joint treatment effects, but do give a frame of reference for evaluating the absolute strength of joints. The mean tensile strength for cores containing no joint was 1,759 kPa (standard deviation (s) = 265 kPa, number of tests (n) = 71). Some treatment conditions resulted in tensile strengths very close to this reference value. For example, high-pressure water and air-water, along with 24-hr drying or drying followed by rewetting resulted in tensile strengths that ranged from 75 to 92 percent of the strength of this value. In contrast, cores taken from Block A, in which there was no surface treatment and the surfaces were kept moist continuously, had a mean tensile strength of 300 kPa, about 16 percent of the tensile strength of its companion intact cores.

Table 7
Mean Tensile Strength of Cores Containing Joints and Not Containing Joints

Moisture Condition	Property	Joint Treatment: None		High-Pressure Water		Air-Water		Air-Water+	
		Type of Specimen							
		Joint	Intact	Joint	Intact	Joint	Intact	Joint	Intact
Wet	Strength, kPa	300	1,870	1,030	2,000	1,140	1,520	1,300	1,560
	Std. error[1], kPa	70	110	70	110	90	110	80	110
	No. of specimens	6	6	6	6	4	5	5	6
Dry	Strength, kPa	820	1,750	1,420	1,840	1,610	1,670	1,020	1,850
	Std. error, kPa	70	110	70	110	70	110	70	110
	No. of specimens	6	6	6	6	6	6	6	6
Dry-rewet	Strength, kPa	680	1,820	1,530	2,030	1,320	1,500	830	1,560
	Std. error, kPa	80	110	90	110	100	110	80	110
	No. of specimens	5	6	4	6	3	4	5	6

[1] Std. error - $s/\sqrt{n}$

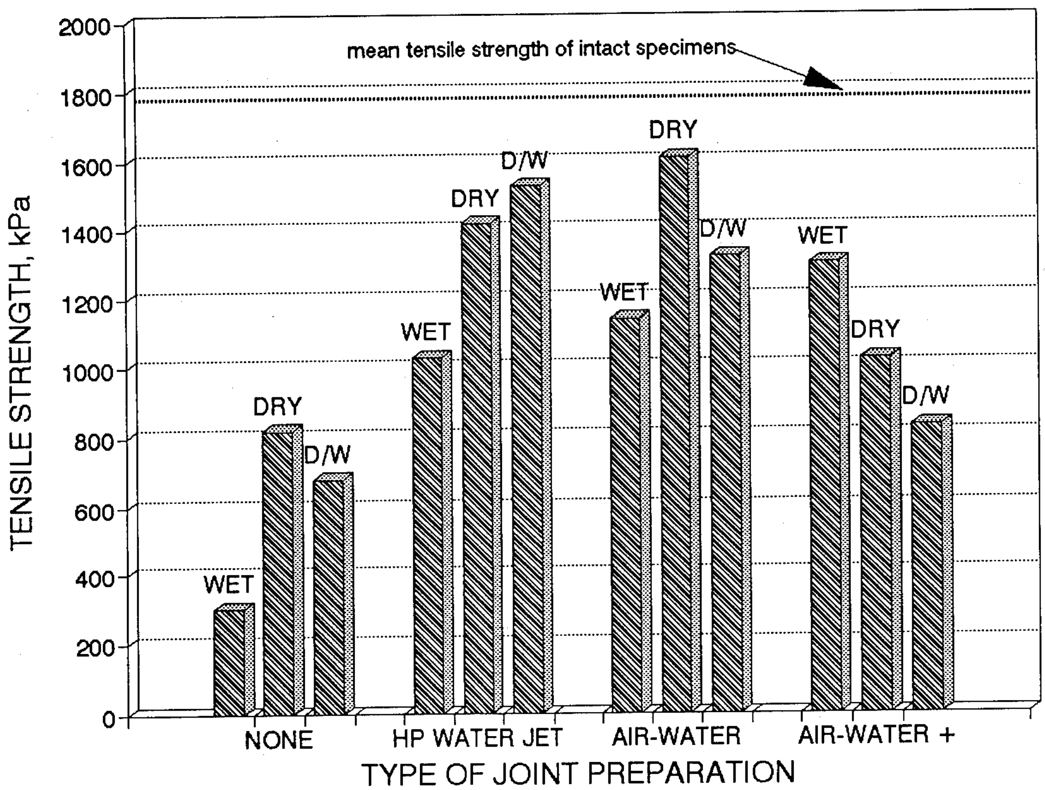

Figure 4. Direct tensile strength

Shear Strength

Maximum

Maximum shear data are summarized in Table 8 and illustrated in Figure 5. Failure envelopes are given in Appendix C. Analysis of variance was not used to analyze these data because the absence of replication makes this a relatively weak statistical method. The regression calculations resulted in standard errors for cohesion values that were useful for making pairwise comparisons of means. Means whose standard errors do not overlap were taken as significantly different at the 5-percent probability level. As with direct tensile test results, both joint preparation and moisture condition were statistically significant variables, and the patterns were similar. However, shear test results indicated that dry joints were clearly stronger than continuously-wet or dry-then-rewetted joints for the no-treatment, high-pressure water, and air-water preparation methods. The shear strengths for the high-pressure water and air-water cleanup methods were indistinguishable from the shear strength of intact specimens (4,577 kPa, s = 284, n = 11). In the case of air-water cutting to extra depth, there was no significant difference among different moisture conditions.

Table 8
Maximum Shear Strength (kPa) of Cores Containing Joints and Not Containing Joints

		Joint Treatment							
		None		High-Pressure Water		Air-Water		Air-Water +	
		Type of Specimen							
Mois. Cond.	Property	Joint	Intact	Joint	Intact	Joint	Intact	Joint	Intact
Wet	Cohesion, kPa	1,500	4,739	2,574	4,434	3,241	5,060	3,703	4,456
	Std error of intercept, kPa	221	710	264	488	431	459	549	368
	ϕ, rad	1.05	0.96	1.08	1.06	0.94	-0.16[1]	0.63	0.58
	No. of specimens	4	4	6	6	6	6	6	6
Dry	Cohesion, kPa	3,411	4,793	4,613	4,765	4,433	4,550	3,240	4,728
	Std error of intercept, kPa	776	559	299	551	296	200	556	436
	ϕ, rad	0.86	0.82	0.59	0.40	0.54	0.47	1.01	0.52
	No. of specimens	6	6	6	6	6	6	6	6
Dry-rewet	Cohesion, kPa	2,314	4,790	3,949	4,257	2,875	3,947	3,555	4,887
	Std error of intercept, kPa	374	473	389	100	499	273	447	236
	ϕ, rad	1.10	1.15	0.66	0.87	0.94	1.12	0.82	0.99
	No. of specimens	6	6	6	6	6	6	6	5

[1] Result was improbable; results from this cell were not used in statistical calculations.

The coefficients of internal friction (ϕ angles) associated with determinations of maximum shear strength were characterized by large standard errors (0.70 rad), so that comparisons among individual values were not significant at P (probability that the conclusion is incorrect and due to random error) = 0.05. Even though specific comparisons of means were not possible, a two-way ANOVA was conducted on the ϕ angles to determine

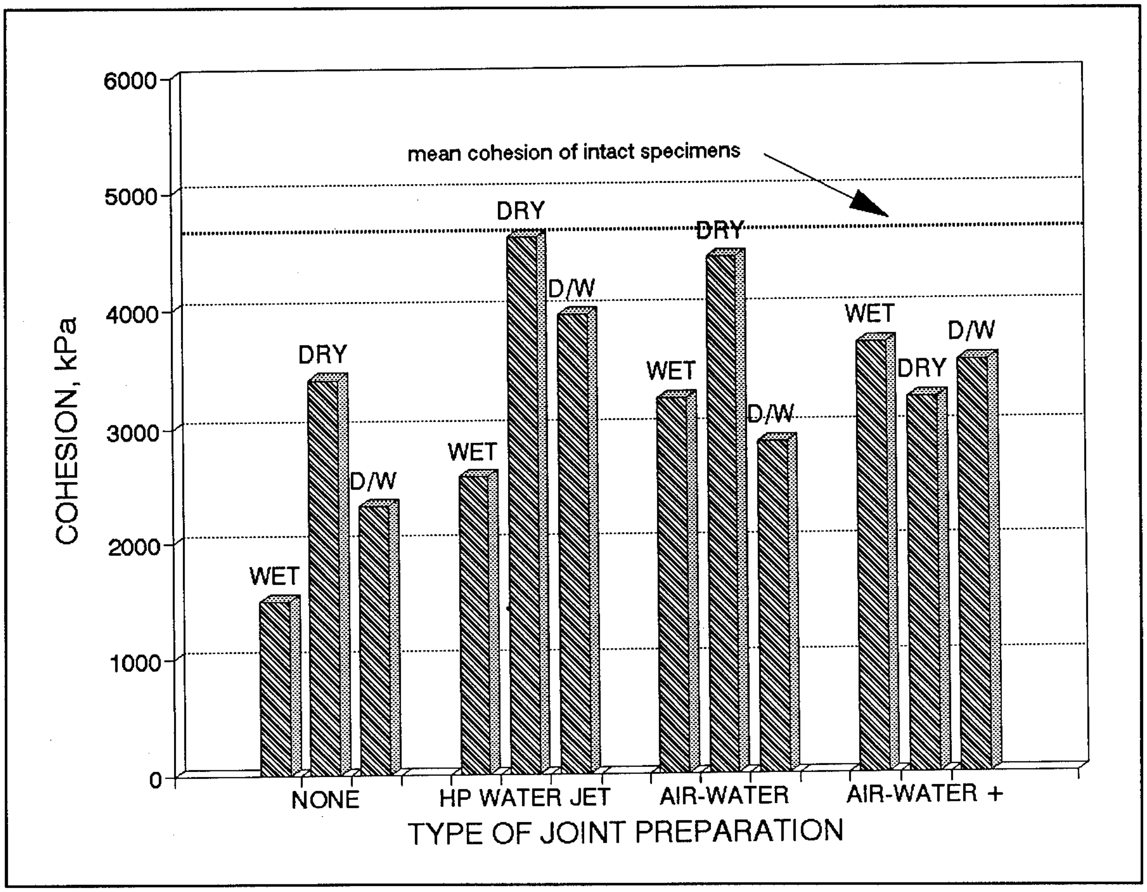

Figure 5. Maximum shear strength

whether there were any general effects. Neither joint treatment or moisture condition were significant variables at P = 0.05 (Appendix D). The mean values of ϕ for jointed specimens was 0.86 $\pm$ 0.12 rad (95 percent confidence interval) and for intact specimens was 0.82 $\pm$ 0.19 rad. These means were not different when compared by Student's t-Test (t) = 0.38, 21 degrees of freedom (df), P = 0.70).

Residual

Residual cohesion values and ϕ angles are summarized in Table 9 and mean strengths are illustrated in Figure 6. Failure envelopes are given in Appendix C. Although most values of residual shear are positive, they were, in most cases, not statistically different from zero, using two standard errors as the comparison criterion. Unlike the ϕ's associated with maximum shear determinations, ϕ's associated with residual shear determinations had a smaller standard error (0.19 rad). Neither joint treatment nor moisture condition were significant when data were analyzed in a two-way ANOVA (Appendix D). Mean values of ϕ for specimens that did not contain a joint were 0.84 $\pm$ 0.10 rad (95-percent confidence interval) and 0.70 $\pm$ 0.03 rad for

Table 9
Residual Shear Strength (kPa) of Cores Containing Joints and Not Containing Joints

Mois. Cond.	Property	None		High-Pressure Water		Air-Water		Air-Water +	
		Joint	Intact	Joint	Intact	Joint	Intact	Joint	Intact
Wet	Cohesion, kPa	83	252	54	-4.5	47	55	32	178
	Std error of intercept, kPa	36	258	34	240	59	98	19	206
	ϕ, rad	0.66	0.93	0.73	1.08	0.72	0.86	0.70	0.84
	No. of specimens	4	4	6	6	6	6	6	6
Dry	Cohesion, kPa	114	292	52	-24	104	29	43	53
	Std error of intercept, kPa	42	138	42	70	25	51	51	77
	ϕ, rad	0.65	0.63	0.82	1.06	0.66	0.96	0.73	0.87
	No. of specimens	6	6	6	6	6	6	6	6
Dry-rewet	Cohesion, kPa	73	381	94	353	61	235	129	367
	Std error of intercept, kPa	58	104	87	37	44	104	50	360
	ϕ, rad	0.65	0.58	0.73	0.59	0.73	0.70	0.68	0.87
	No. of specimens	6	6	6	6	6	6	6	6

Joint Treatment / Type of Specimen

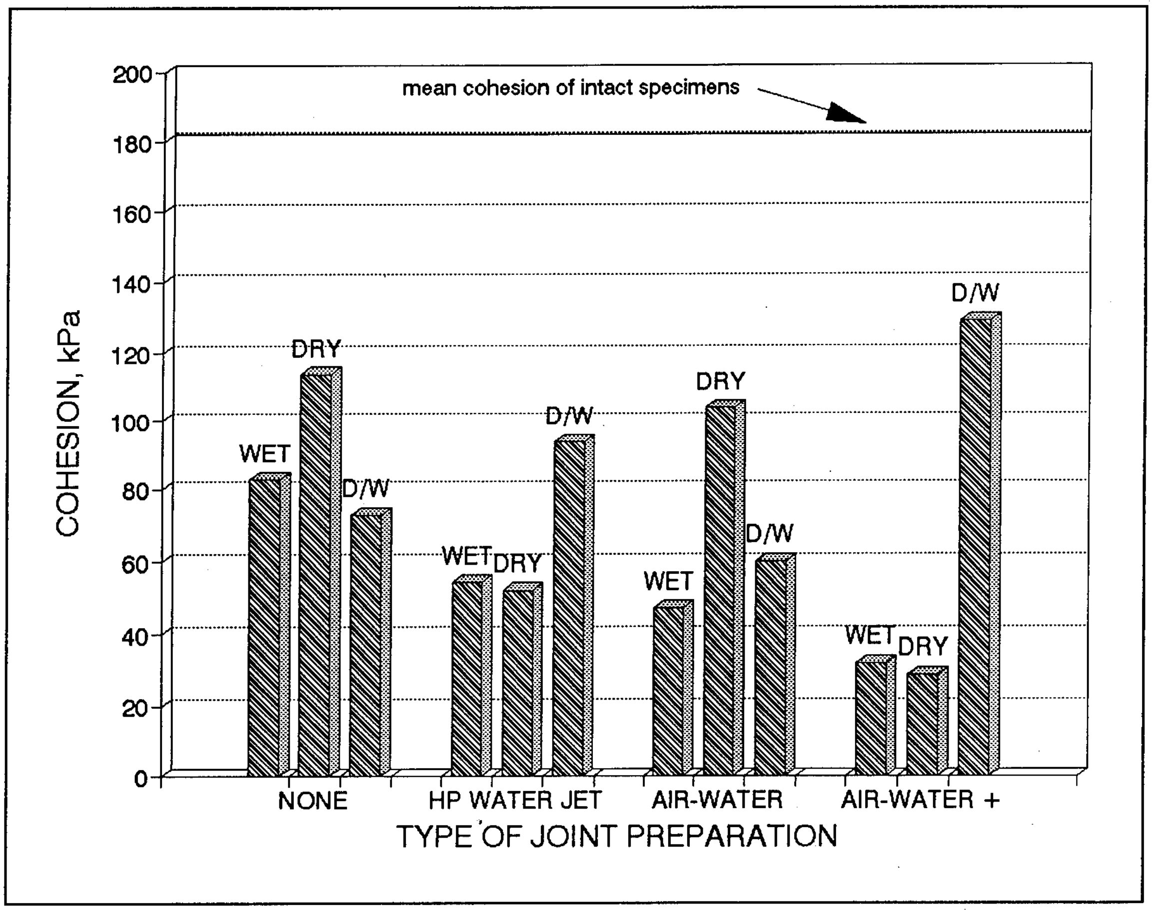

Figure 6. Residual shear strength

specimens that did contain a joint. These means were significantly different when compared by Student's t-Test ($t = 2.41$, 22 df, $P = 0.02$).

Permeability

Permeability results are summarized in Tables 10 and 11. Table 10 summarizes data that have not been adjusted for the length of joint in the core. The purpose of these data is to compare the permeability of specimens containing joints with specimens not containing joints. This will give some indication of the relative contribution of the joints to the permeability. In three of the four comparisons (no treatment, high-pressure water, and air-water+), the specimens containing joints had higher permeabilities than specimens containing no joints, but the difference was less than an order of magnitude. In the fourth comparison (air-water), the permeabilities were about the same.

Table 10
Mean Permeability ($\times 10^{-20}$) of Specimens Containing Joints and Specimens Not Containing Joints (Values are in units of m^2. Standard errors are in parentheses.)

Moisture Condition	Joint Treatment							
	None		Water		Air-Water		Air-Water +	
	Mean Permeability $\times 10^{-20}$ (Standard Error[1]), m^2							
	Joint	Intact	Joint	Intact	Joint	Intact	Joint	Intact
Wet	130 (53.0)		97 (22.2)	39 (2.4)	2.5 (0.77)		95 (7.5)	
Dry	48 (12.0)	13 (5.2)	85 (8.0)		17 (4.8)	21 (6.2)	122 (8.3)	
Dry-rewet	130 (36.4)		108 (22.8)		57 (7.9)		267 (44.8)	91 (34.0)

[1] Std. error - $s/\sqrt{n}$

Data in Table 11 have been corrected for the length of joint in the cross section of each specimen, allowing for comparisons among treatment and moisture conditions. Data were analyzed by a two-way analysis of variance (Appendix E). Comparison of means among treatment conditions is illustrated in Figure 7. Both joint treatment and moisture condition were significant effects in the analysis. There was also a significant interaction effect between these two variables. From inspection of Figure 7, it is clear that the statistical significance of the analysis is caused by three treatment conditions. These were: the wet and the dry conditions with air-water cutting which showed lower than average permeability, and the dry-then-rewet condition with air-water cutting to extra depth, which showed higher-than-average permeability. The other conditions appear to represent a single population of test results.

Table 11
Mean Permeability ($\times 10^{-20}$) of Cores Containing Joints

Moisture Condition	Joint Treatment			
	None	Water	Air-Water	Air-Water +
	Mean Permeability $\times 10^{-20}$ (Standard Error), m^2/m			
	Joint	Joint	Joint	Joint
Wet	1,345 (3.85)	1,258 (2.56)	28 (0.54)	1,045 (2.79)
Dry	488 (3.85)	853 (2.56)	360 (0.54)	1,233 (2.79)
Dry-rewet	1,287 (3.85)	1,121 (2.56)	572 (0.54)	2,700 (2.79)

Note: (Values are in units of m^2 per meter of joint in the cross section of the specimen. Standard errors are in parentheses.)

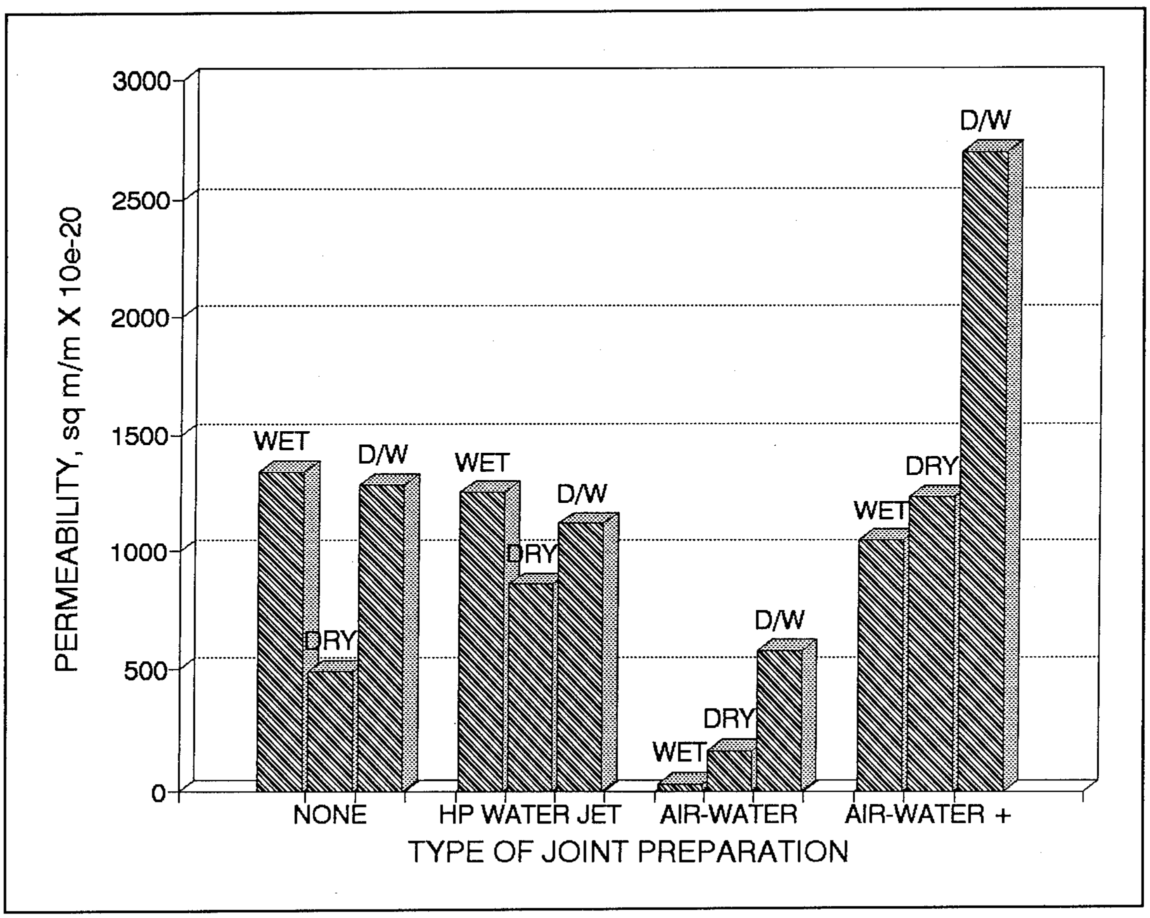

Figure 7. Permeability per length of joint

4 Discussion of Results

The tests that directly measured the physical integrity of the joint (tensile-strength and shear strength tests) tended to support the hypothesis that high-pressure water and air-water cleanup methods resulted in stronger joints. There was no apparent increase in tensile or shear properties when air-water cutting to a greater depth was employed. Significantly lower tensile and shear strength were indicated when no joint cleanup was used.

The physical integrity was further enhanced if the joint was dry or had been allowed to dry followed by a rewetting. Dry joints also were stronger in specimens that had no cleaning prior to placement of the second lift, although this lack of joint preparation clearly resulted in the weakest joints. Continuously wet concrete was the worst moisture condition except when air-water cutting to extra depth was used as the joint cleaning procedure, in which it was the highest-strength condition.

That dry joints give strong bonds is plausible, and two possible explanations follow: (a) A surface that had been kept continuously moist would absorb no water left on the surface from curing nor any surplus water from the fresh concrete. Any excess water on the surface could cause a zone of high water-cement ratio (w/c) paste at the interface between the two concretes; (b) A dry surface would tend to absorb water from the fresh concrete, creating a lower w/c paste in the region of the interface. It is not clear why these same phenomena would not also apply to the air-water cutting to extra depth.

The large standard error associated with the ϕ angles in the maximum shear determinations makes it more difficult to draw conclusions from these data. However, the observation that there was no significant difference between the ϕ angle of the jointed specimens and the intact specimens indicates that the integrity of a properly prepared joint can be similar to that of intact concrete.

The standard error associated with the ϕ angles in the residual shear determinations was smaller than that of the maximum shear determinations, making it easier to identify differences among test conditions. It might be expected that the ϕ angles would be more consistent on the residual tests, because they are essentially a measure of the sliding friction along a fractured plane. The lower ϕ angle indicated by the jointed specimens probably results because of a smoother surface with fewer protruding coarse aggregate particles than on the intact specimens.

In general, permeabilities of jointed specimens did not differ from permeabilities of intact concrete by very much. However, interpretation of differences among treatment conditions is difficult. Even though there were a few comparisons among treatment conditions that were statistically significant, there appeared to be no patterns for which plausible causes could be identified. Also, there appeared to be no correlations related to the patterns developed from tensile and shear strength results. Therefore, no conclusions concerning the effect of various joint cleanup or moisture conditions can be drawn from the permeability test results.

One source of caution in interpreting the results of this work is that each surface preparation and moisture condition combination was represented by only one test block. The replication that was used for statistical analysis reflected variation among the cores taken from that single block. So, if there was some unusual, but unknown feature about the preparation of one of the test blocks that was unrelated to the principal variables of interest, then spurious conclusions could be drawn from the statistics. However, the interpretation of strength results generally does not depend critically on results from one block, therefore, is reasonably robust with respect to this sampling problem.

One other source of caution in interpreting the results of this work is the reference to "dry" surfaces. None of the surfaces described as "dry" were exposed to high temperatures and low relative humidities for relatively long periods of time, as might occur in construction. No "dry" surface was allowed to dry at a temperature greater than approximately 30 °C, or at a relative humidity lower than approximately 40 percent, nor for a time greater than 24 hr. Hence, if one wishes to get the performance described herein as obtained with "dry" surfaces and the actual surfaces are drier than described above, they should be rewetted and allowed to dry no more than described. It should also be noted that all the concrete used in these tests had 100 kg of water per m^3 of concrete or a water-cementitious material (w/c+m) ratio of 0.55 by mass. If a lower water content or lower w/c+m concrete were used, there might be very little continuous capillary space in the paste. Therefore, loss of water from the near surface of the lower lift would be difficult to achieve and to replace. A concrete of w/c+m = 0.55 will have no capillary continuity after approximately 6 months, but one of 0.4 w/c+m can lose capillary continuity in approximately 3 days of moist curing.

5 Conclusions and Recommendations

Conclusions

The test results indicate that good bond strengths are produced when horizontal construction joints are cleaned by high-pressure water cutting or by air-water cutting. The results also indicated that the surface is adequately cleaned when the visible laitance has been removed, and fine and coarse aggregate particles are exposed. It is not necessary to remove material until the coarse aggregate particles are undercut.

The test results also indicated that better bond strengths are produced when the joint surface is allowed to dry approximately 24 hr immediately prior to placement of the next lift of concrete. In most instances, higher bond strengths were obtained when the joint surface was dry to this extent at the time of placement of the next lift. However, even when the joint surface was remoistened immediately prior to placement of the next lift, the joint strengths were higher than when the joints were kept continuously moist.

The concrete mixture used in this program contained a mortar content within the range recommended by ACI 211.1, "Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete" (ACI 1992), for concrete mixture containing 75-mm NMS aggregate. The mortar content was sufficient to fill voids between the coarse aggregate particles and the voids in the prepared lower surface.

Recommendations

Method of cleaning

CWGS-03305, "Mass Concrete" (Headquarters, Department of the Army 1992) states "Concrete surfaces to which concrete is to be bonded shall be prepared for receiving the next lift or adjacent concrete by cleaning by sandblasting, high-pressure water jet, or air-water cutting...Regardless of the method used, the resulting surface shall be free from all laitance and inferior concrete so that clean, well-bonded coarse aggregate particles are exposed uniformly over the lift surface. Application of the joint treatment method shall be such that the edges of the larger particles of aggregate are not undercut." The test results described above support this guidance, and no change is recommended, other than inserting "visible" before "laitance" since removal of laitance can only be to the extent it can be seen.

Moisture condition

CWGS-03305, "Mass Concrete" (Headquarters, Department of the Army 1992) states "The surface of the construction joint shall be kept continuously wet for the first 12 hr of the 24 hr prior to placing concrete, except that the surface shall be damp with no free water at the time of placement." The test results described above generally indicate that a stronger bond will result when the joint surface is dry at the time of placement. It is recommended that consideration be given toward revising current guidance to permit placement of concrete on a dry surface. The following revision is suggested: The surface of the construction joint shall be kept continuously wet for the first 24 hr of the 48 hr prior to placing concrete. The surface of the construction joint shall then be allowed to dry for the 24 hr immediately prior to placing concrete, and the fresh concrete shall be placed on the dry surface.

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a. Designation C 39-86. "Standard test method for compressive strength of cylindrical concrete specimens."

b. Designation C 42-90. "Standard test method for obtaining and testing drilled cores and sawed beams of concrete."

c. Designation C 127-88. "Standard test method for specific gravity and absorption of coarse aggregate."

d. Designation C 128-88. "Standard test method for specific gravity and absorption of fine aggregate."

e. Designation C 136-84. "Standard method for sieve analysis of fine and coarse aggregates."

f. Designation C 138-81. "Standard test method for unit weight, yield, and air content (gravimetric) of concrete."

g. Designation C 143-90. "Standard test method for slump of portland cement concrete."

h. Designation C 150-92. "Standard specification for portland cement."

i. Designation C 192-90. "Standard test method for making and curing concrete test specimens in the laboratory."

j. Designation C 231-91. "Standard test method for air content of freshly mixed concrete by the pressure method."

k. Designation C 311-92. "Standard test method for sampling and testing fly ash or natural pozzolans for use as a mineral admixture in portland cement concrete."

l. Designation C 511-85. "Standard specification for moist cabinets, moist rooms, and water storage tanks used in the testing of hydraulic cements and concretes."

m. Designation C 618-92. "Standard specification for fly ash and raw or calcined natural pozzolan for use as a mineral admixture in portland cement concrete."

n. Designation E 380-91. "Standard practice for the use of the international system of units."

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Appendix A
Photographs of Cleaned Surfaces

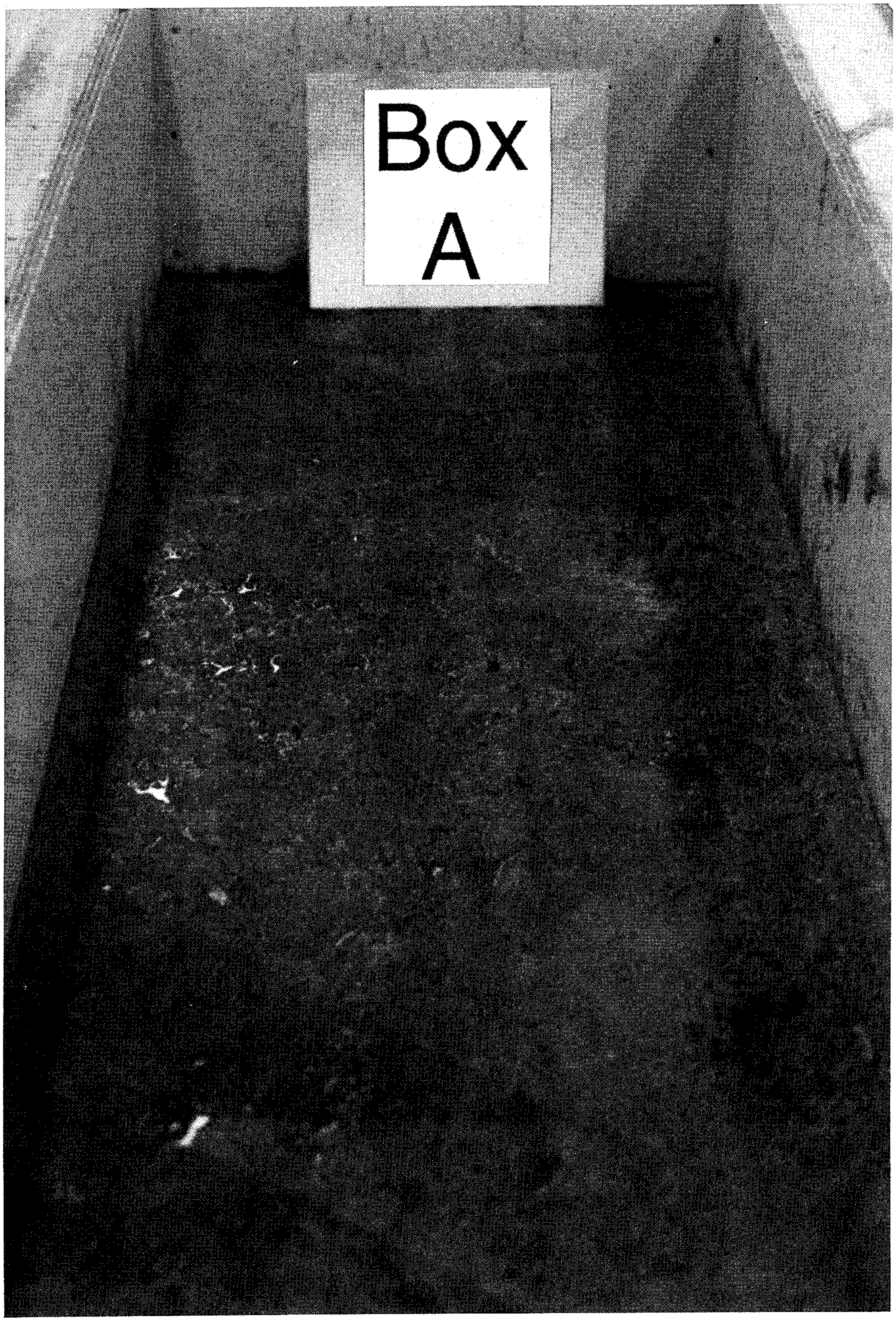

Figure A1. Joint surface of Block A, no joint cleanup, continually wet

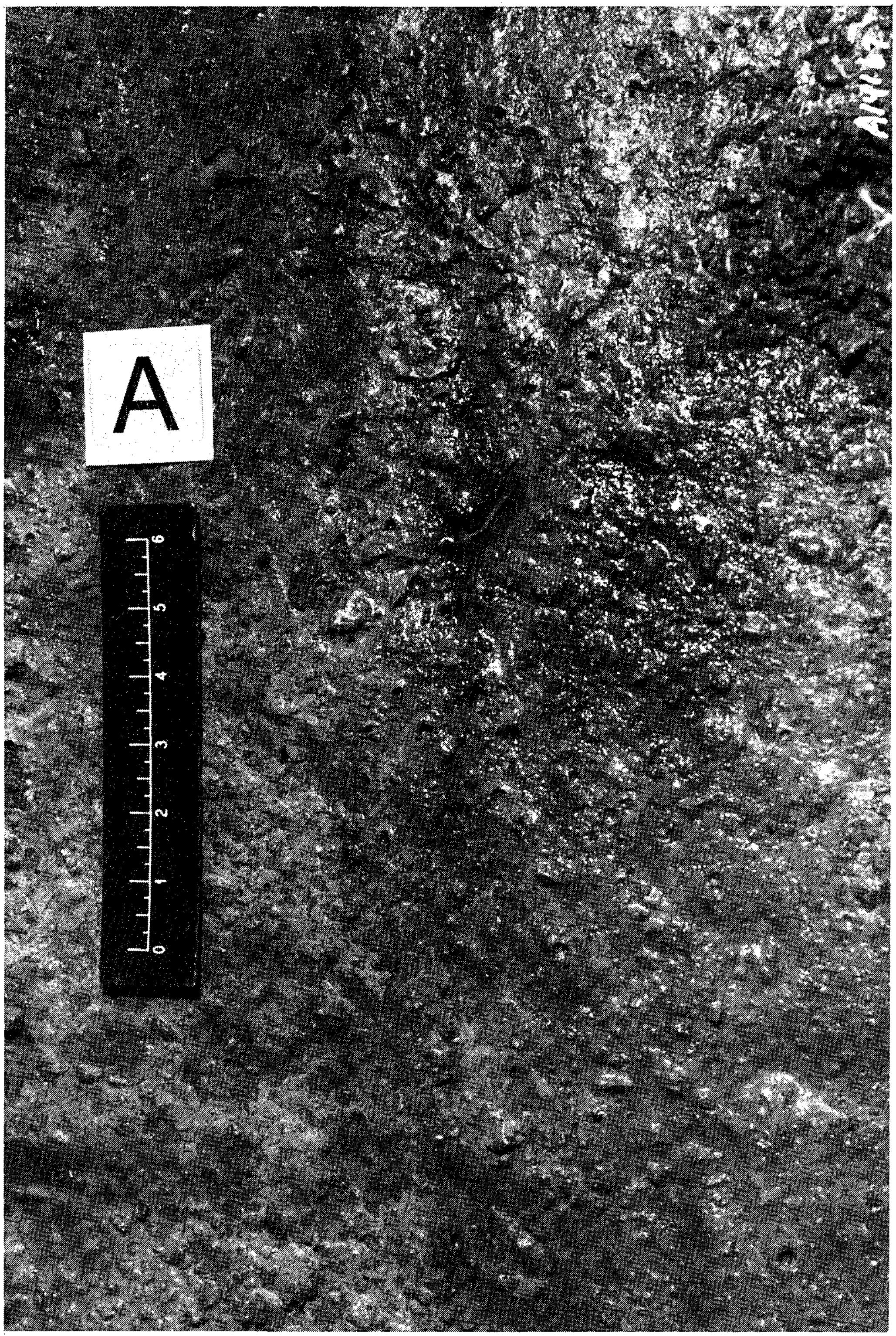

Figure A2. Close-up of joint surface of Block A, no joint cleanup, continually wet

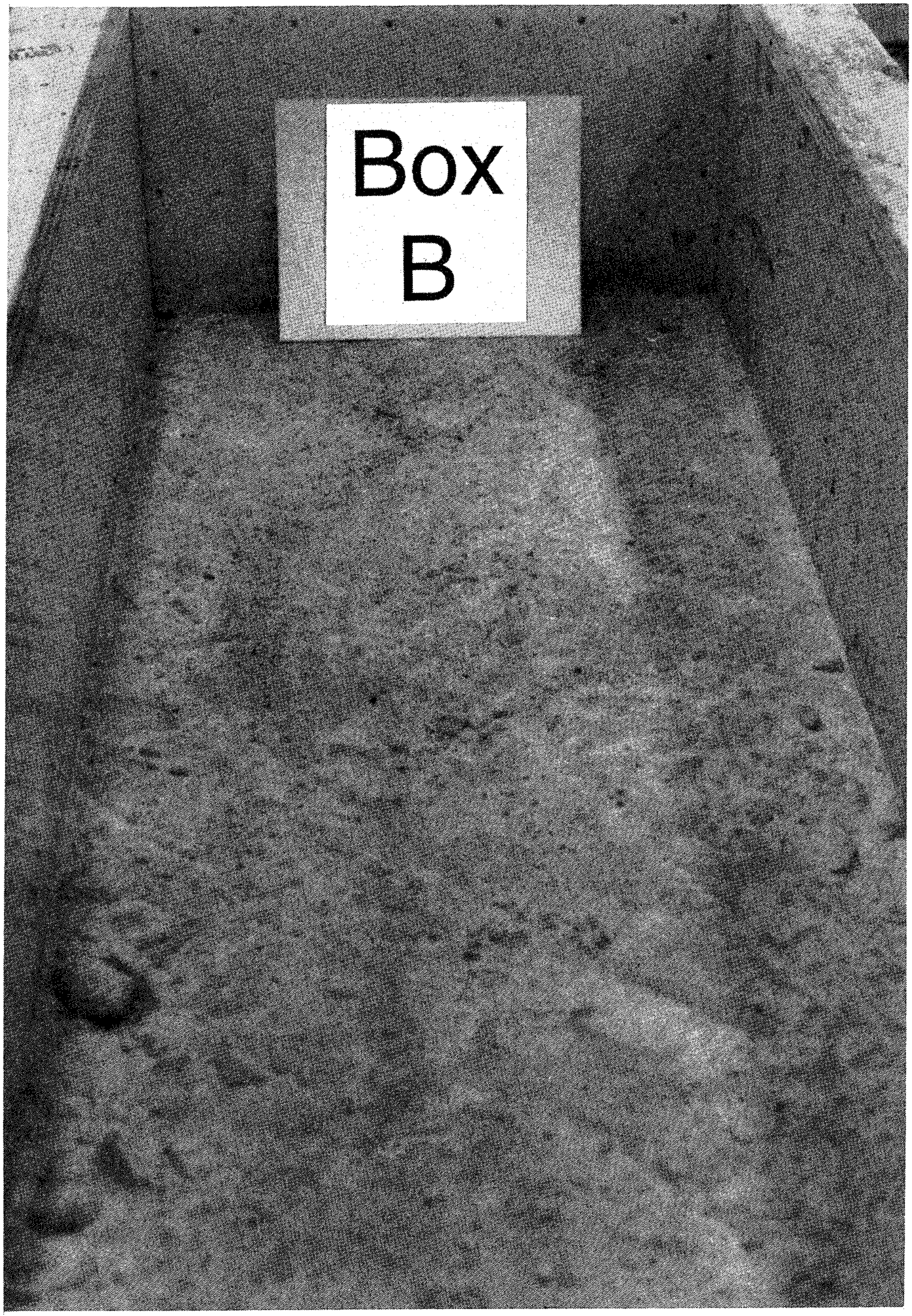

Figure A3. Joint surface of Block B, no joint cleanup, dry

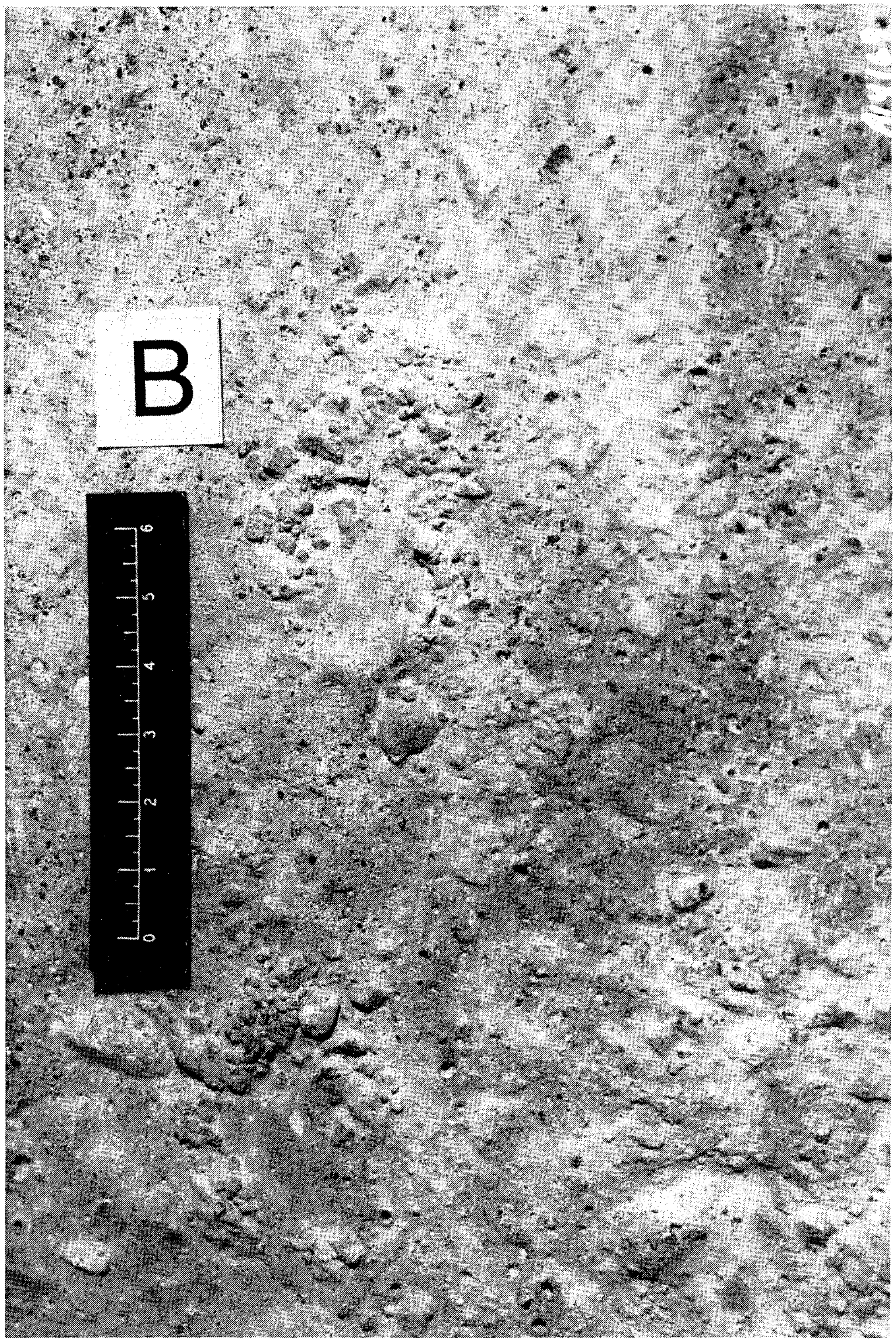

Figure A4. Close-up of joint surface of Block B, no joint cleanup, dry

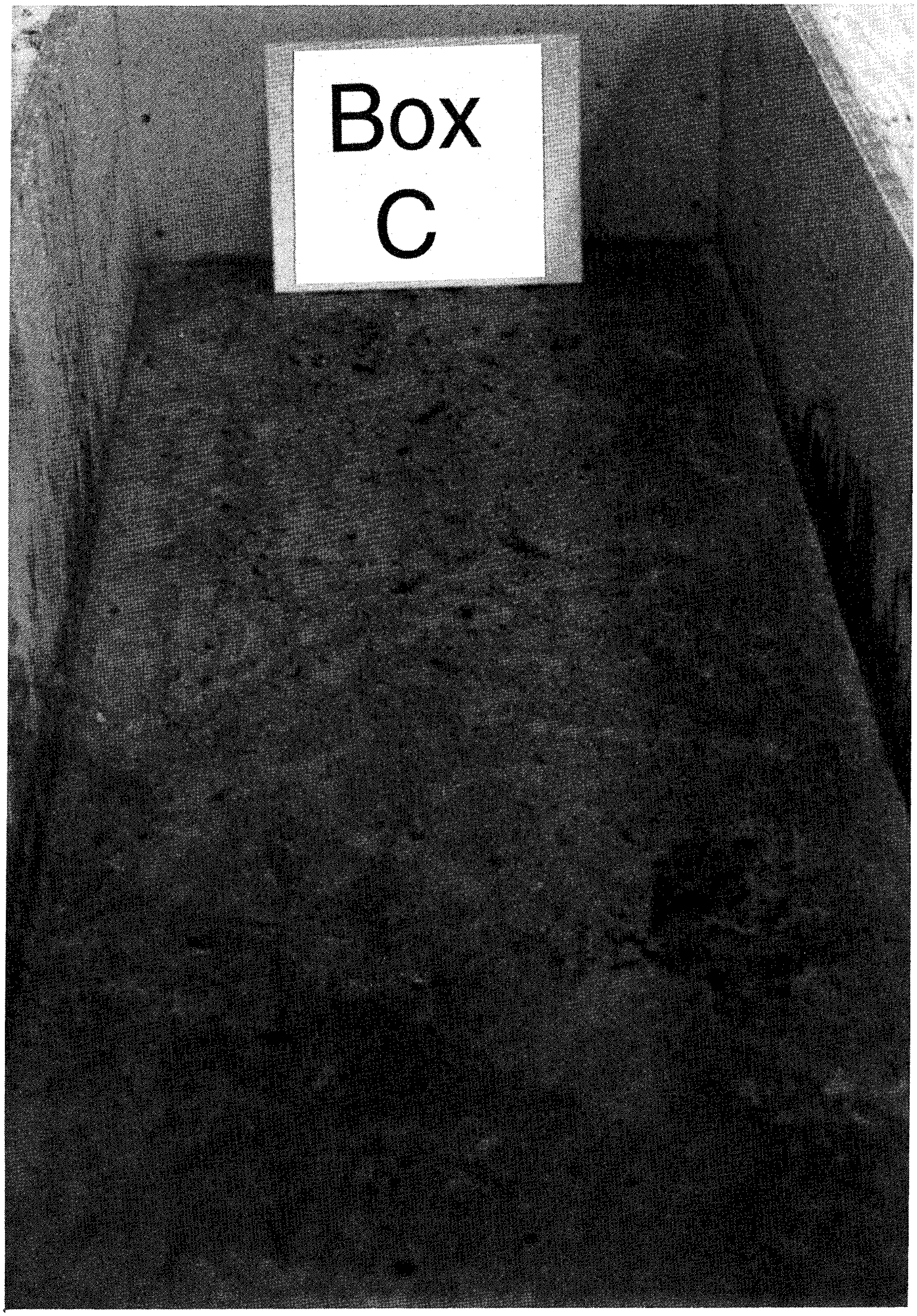

Figure A5. Joint surface of Block C, no joint cleanup, dry then rewet

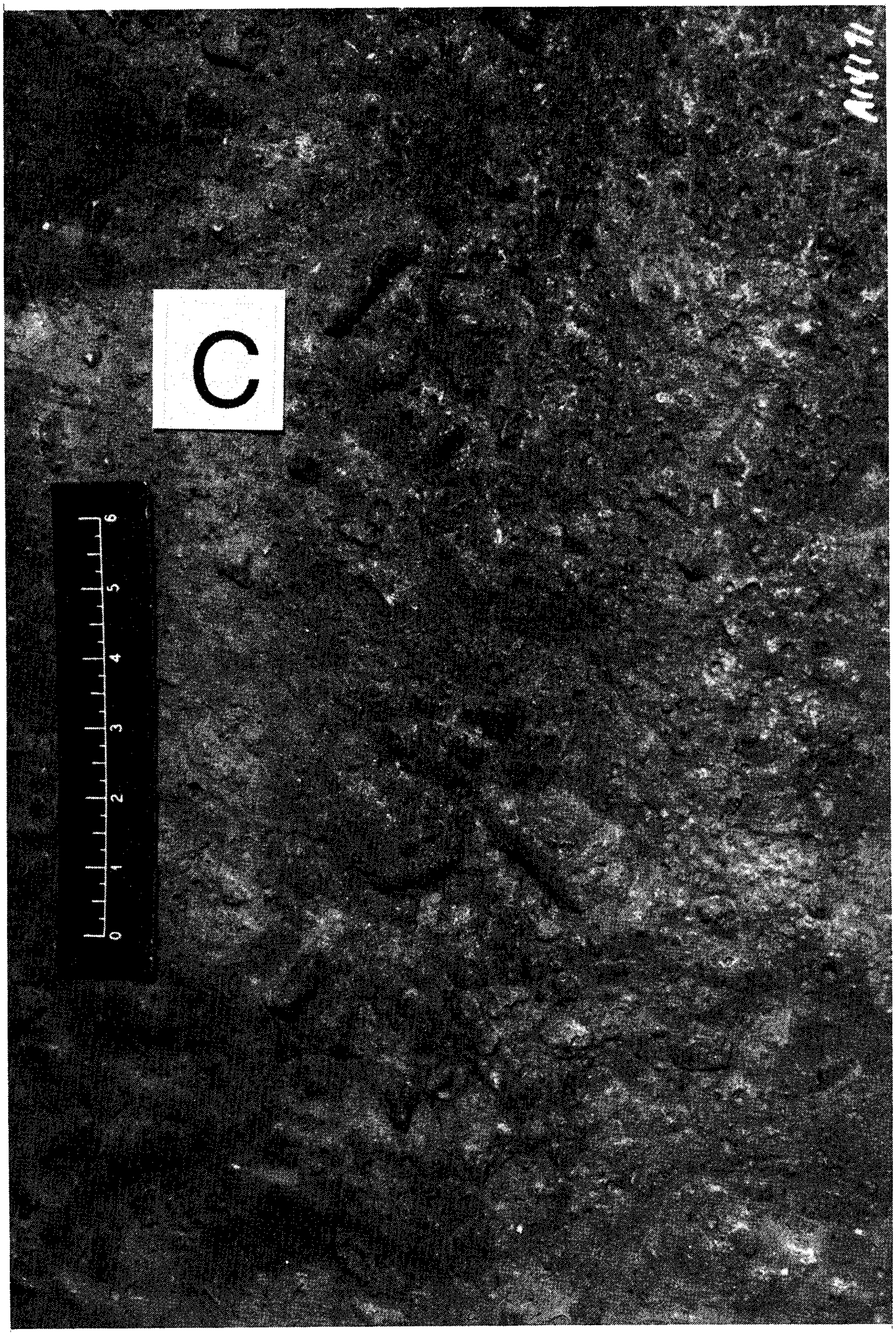

Figure A6. Close-up of joint surface of Block C, joint cleanup, dry then rewet

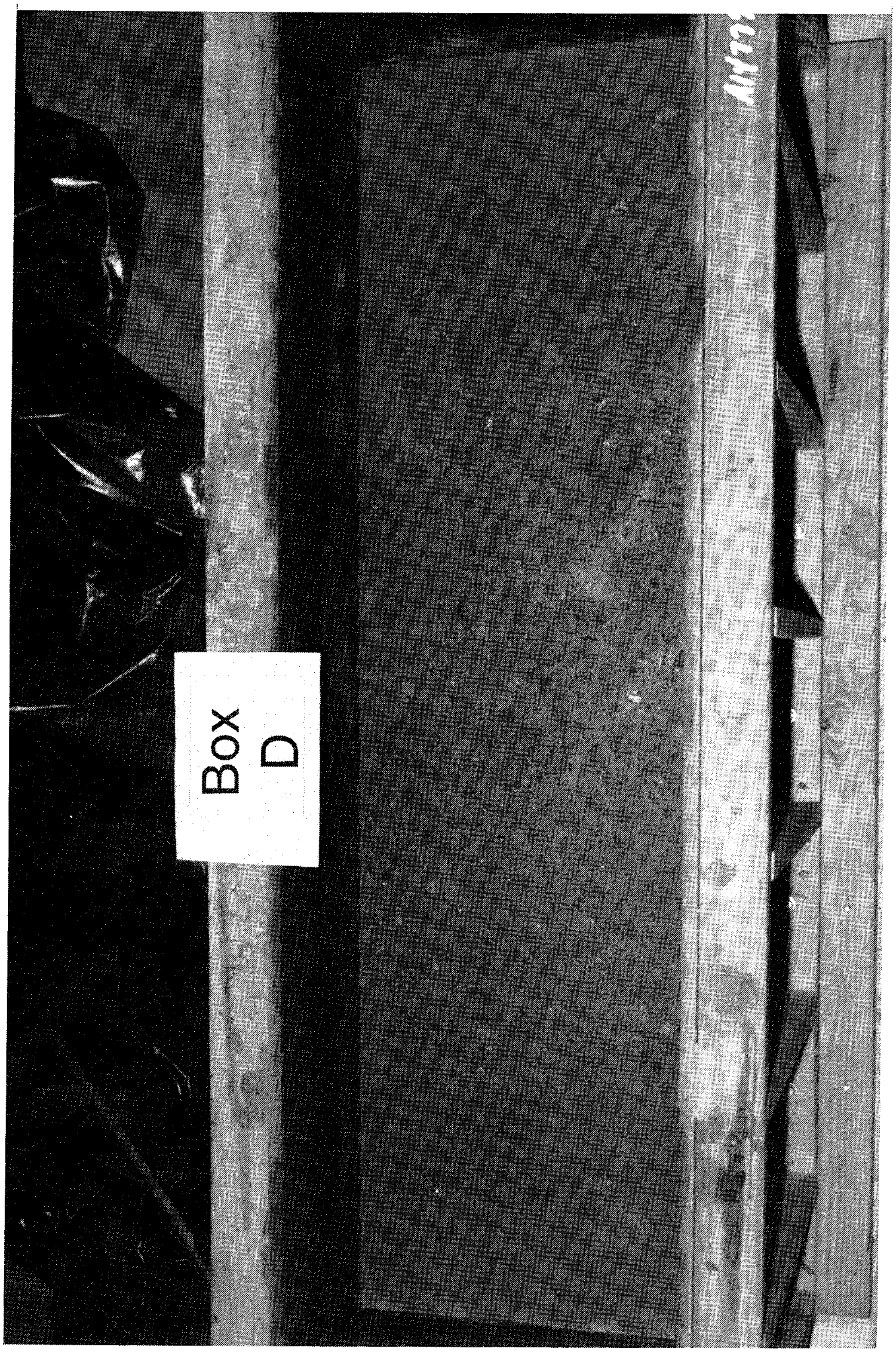

Figure A7. Joint surface of Block D, high-pressure water jet, continually wet

Figure A8. Close-up of joint surface of Block D, high-pressure water jet, continually wet

Figure A9. Joint surface of Block E, high-pressure water jet, dry

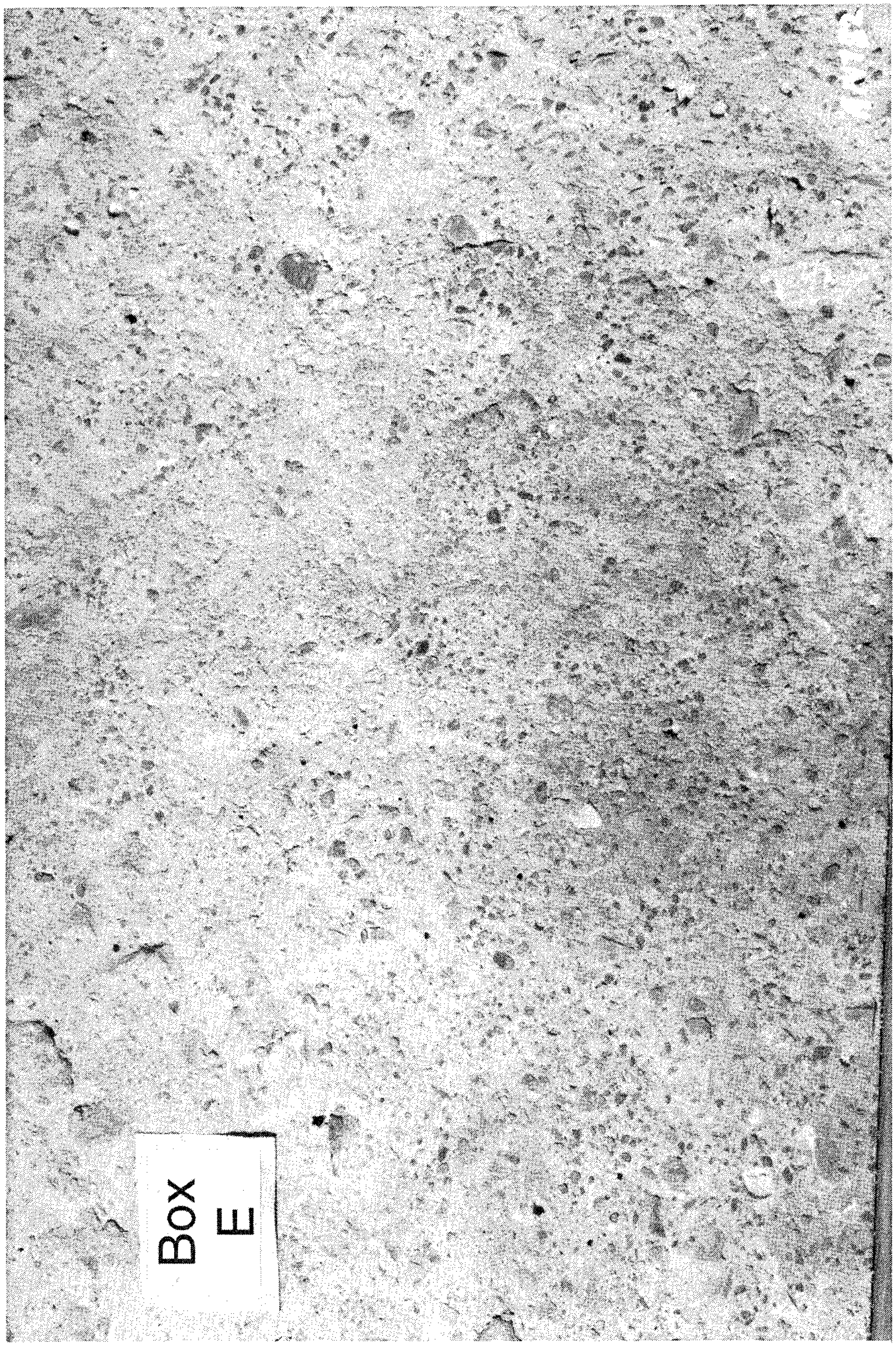

Figure A10. Close-up of joint surface of Block E, high-pressure water jet, dry

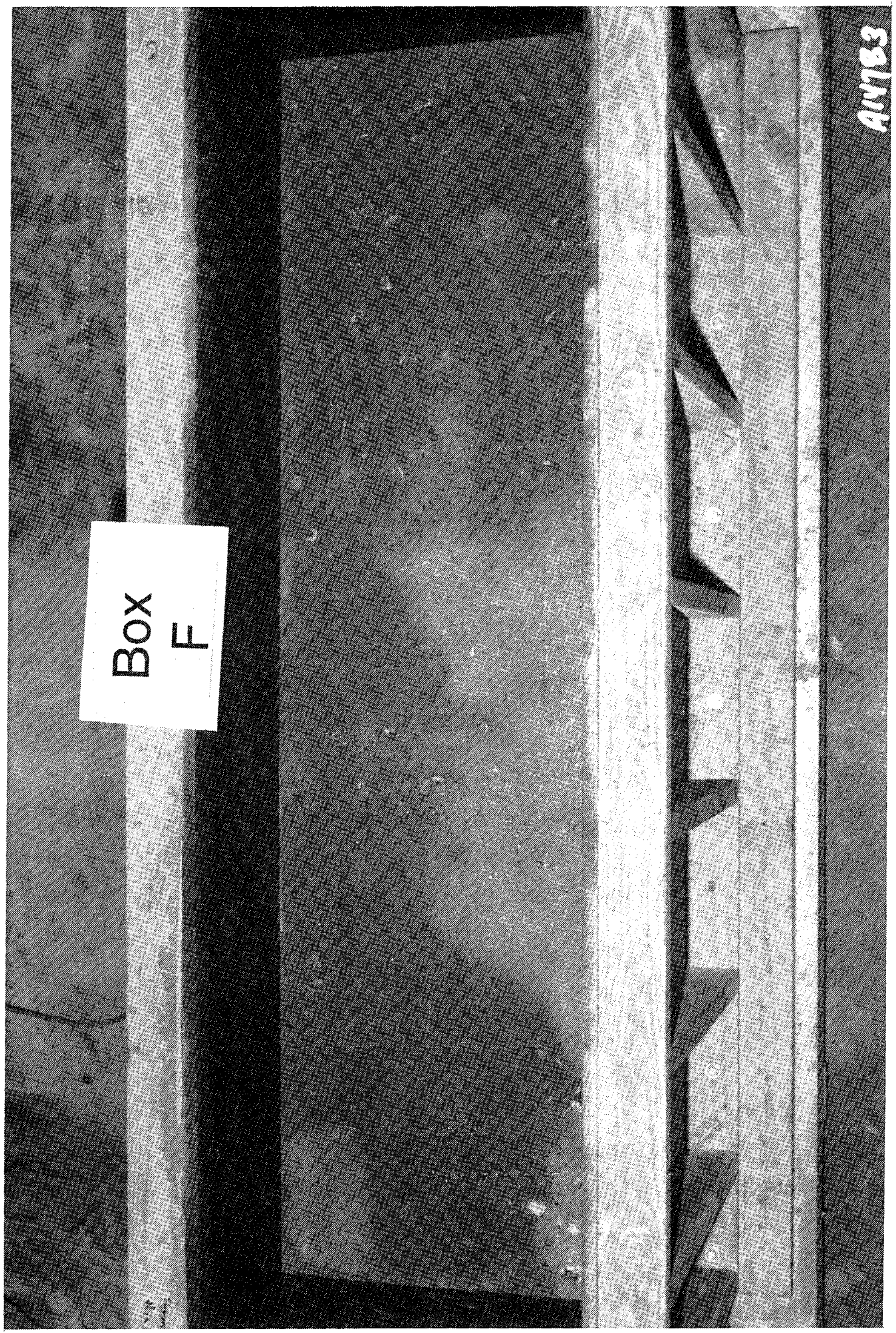

Figure A11. Joint surface of Block F, high-pressure water jet, dry then rewet

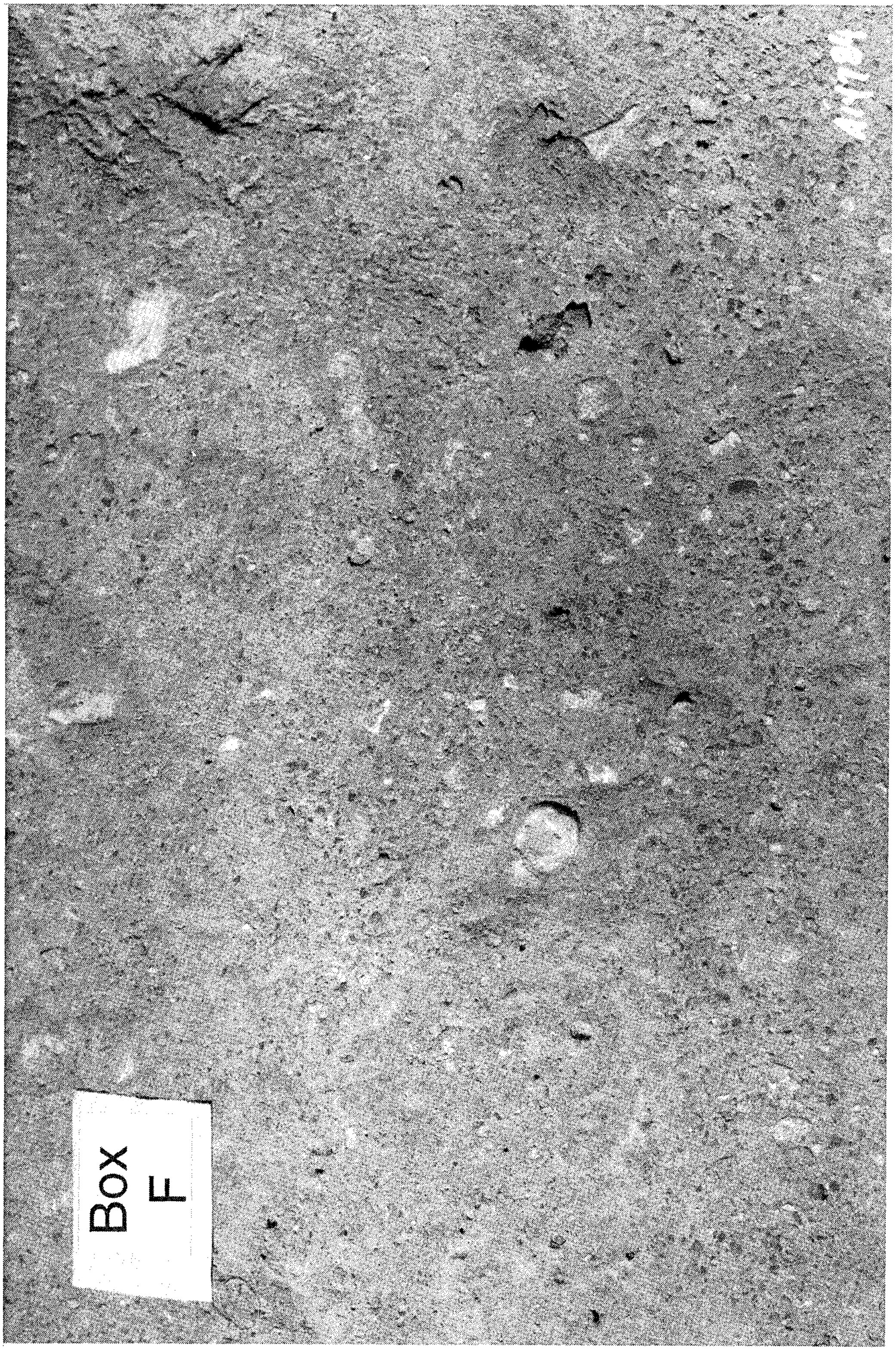

Figure A12. Close-up of joint surface of Block F, high-pressure water jet, dry then rewet

Figure A13. Joint surface of Block G, air-water cutting, continually wet

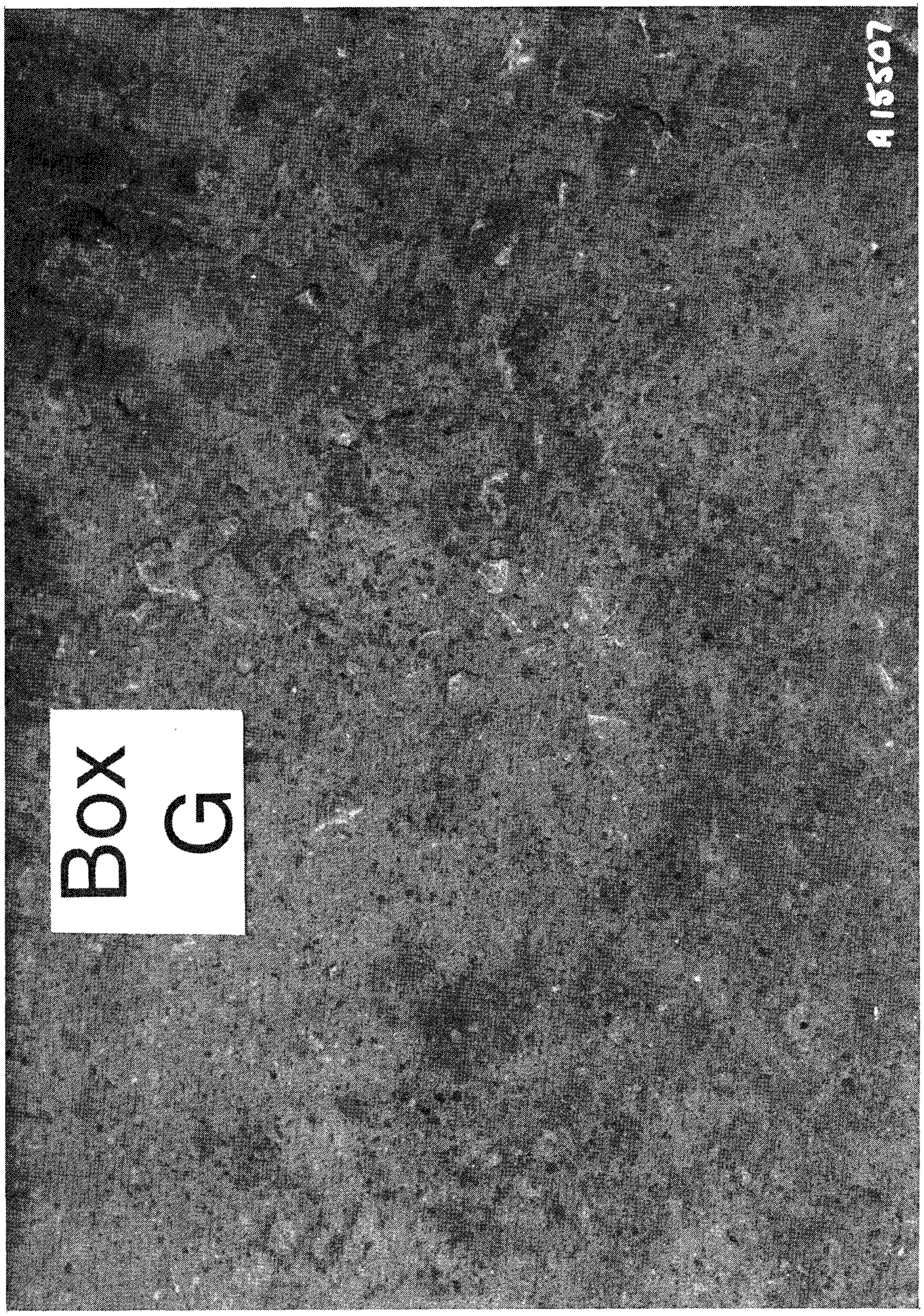

Figure A14. Close-up of joint surface of Block G, air-water cutting, continually wet

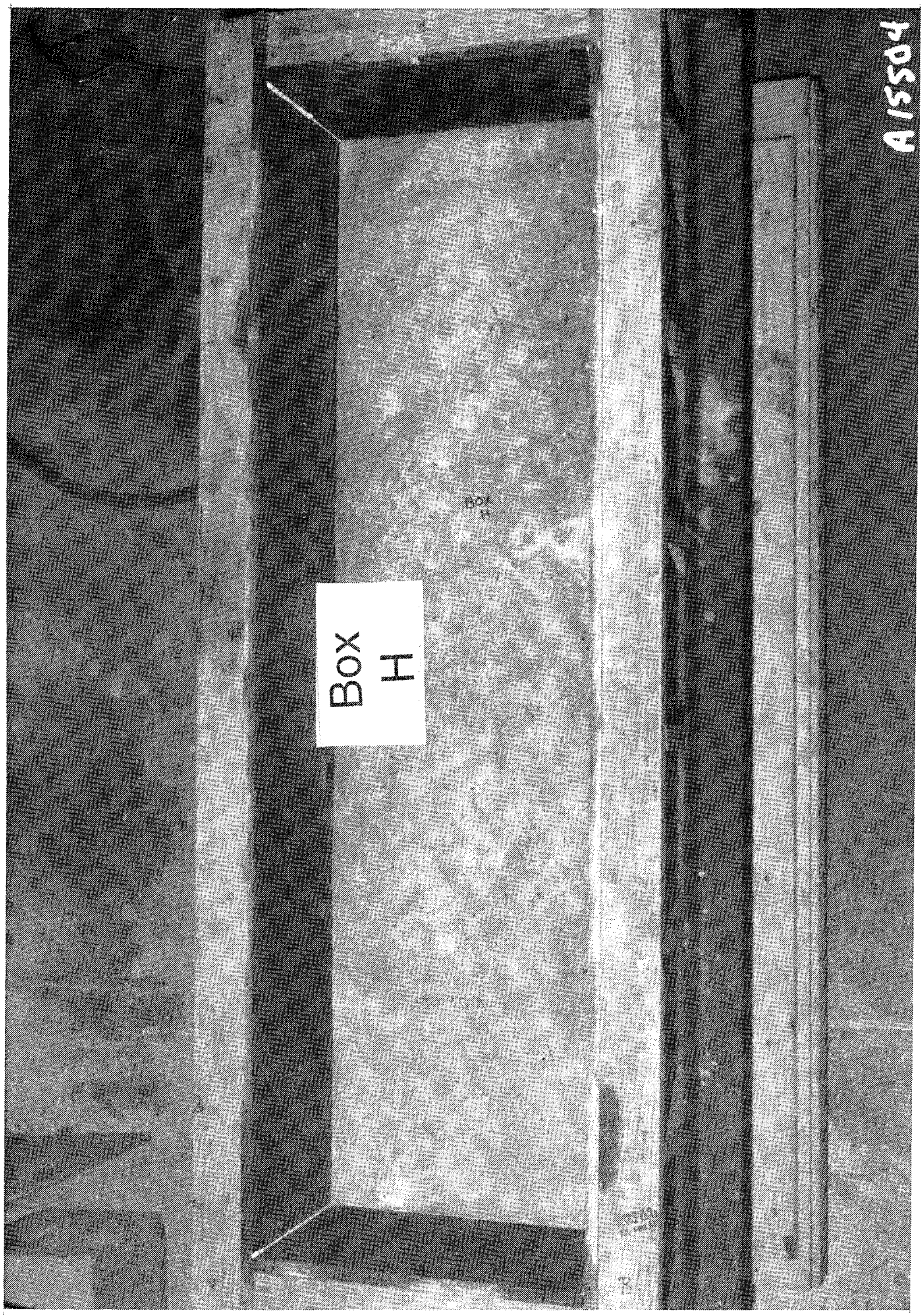

Figure A15. Joint surface of Block H, air-water cutting, dry

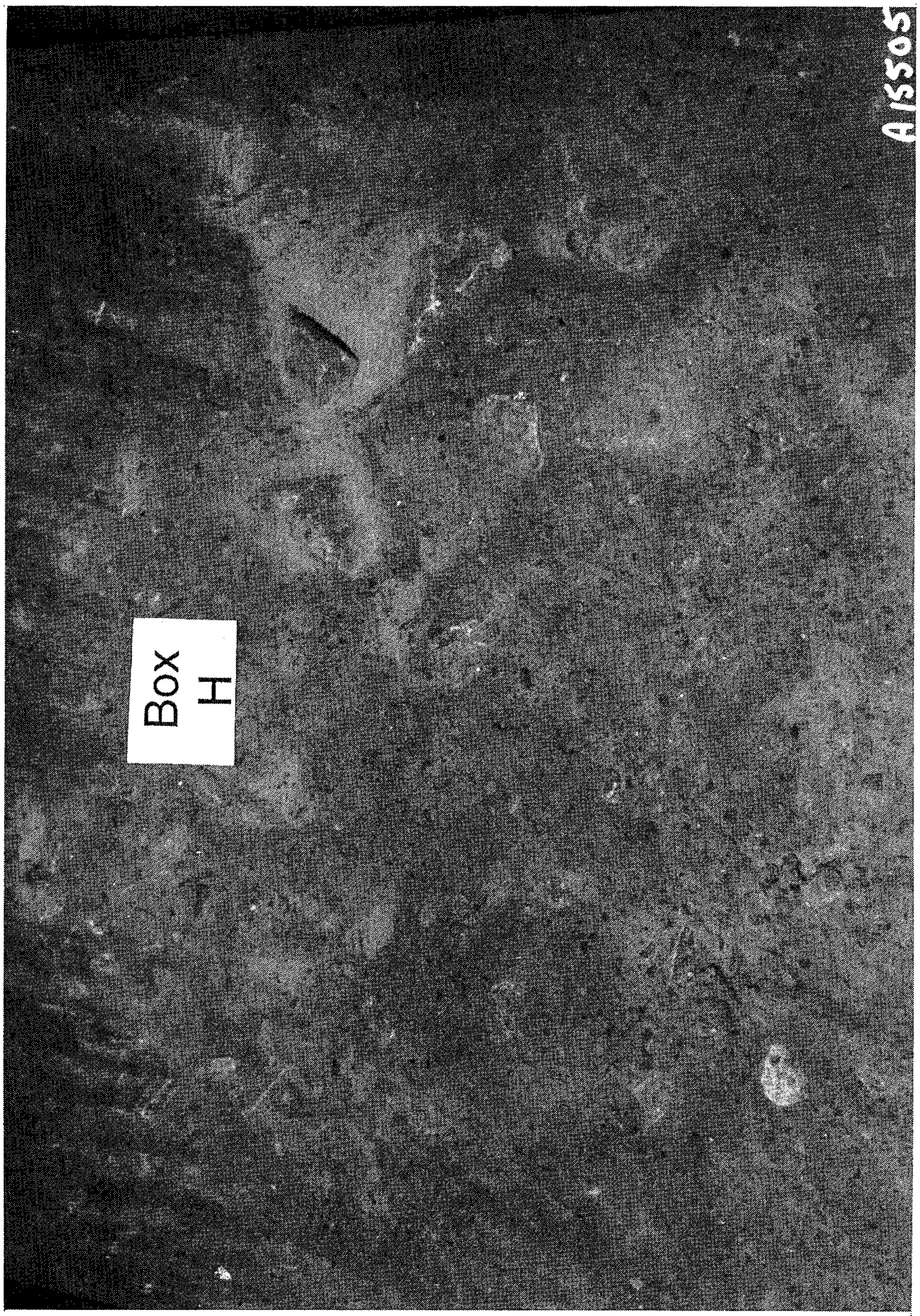

Figure A16. Close-up of joint surface of Block H, air-water cutting, dry

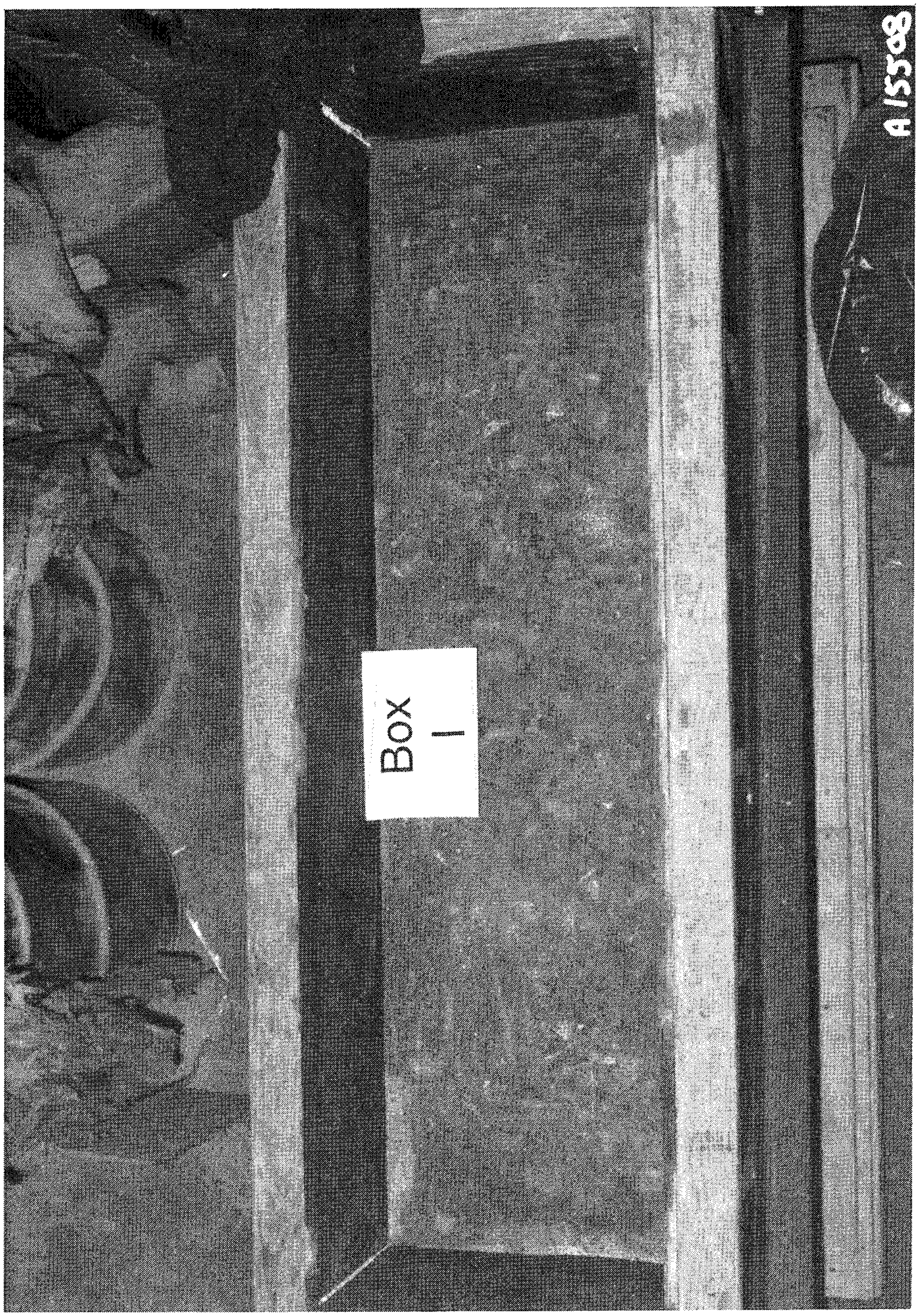

Figure A17. Joint surface of Block I, air-water cutting, dry then rewet

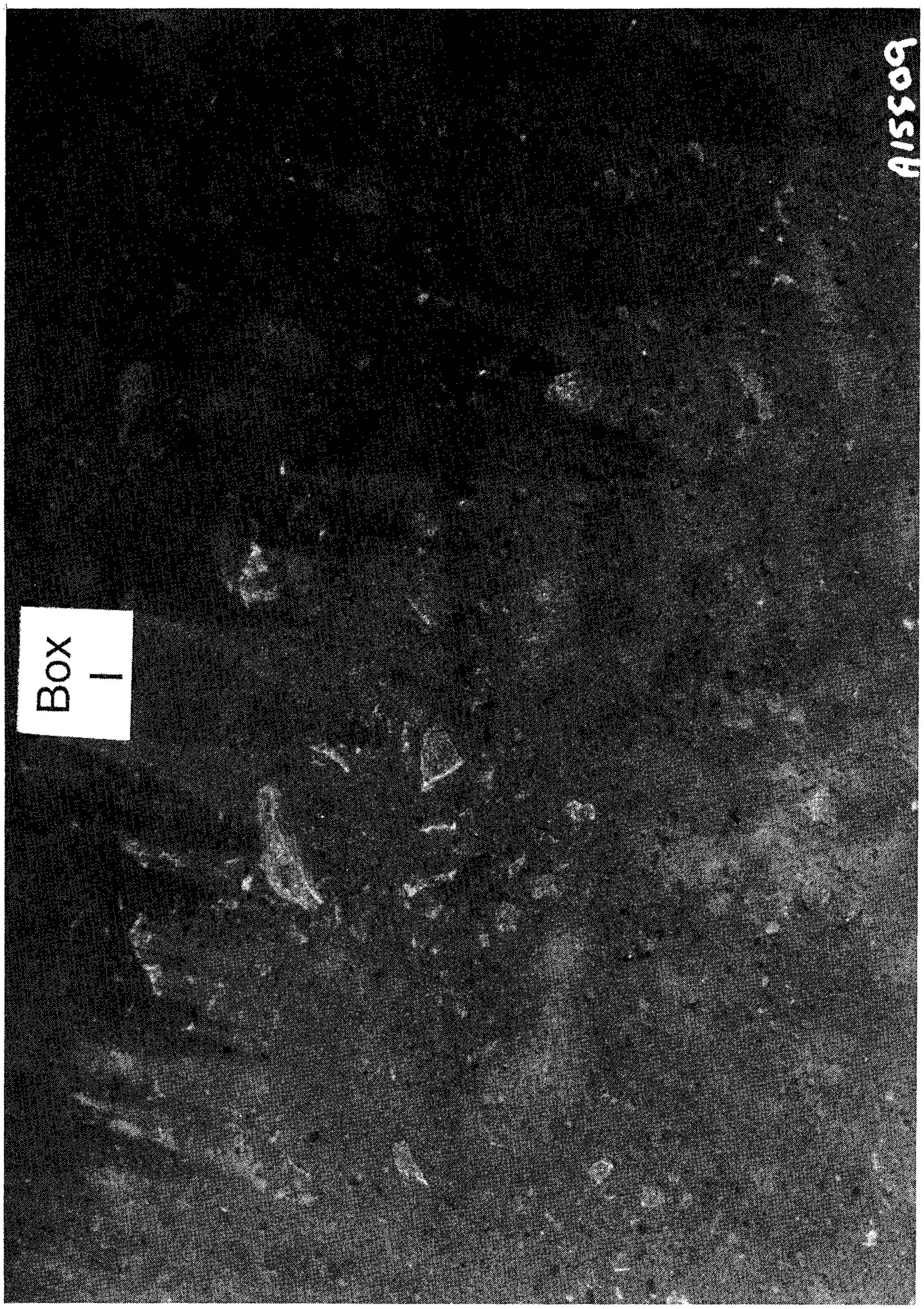

Figure A18. Close-up of joint surface of Block I, air-water cutting, dry then rewet

Figure A19. Joint surface of Block J, air-water cutting (extra depth), continually wet

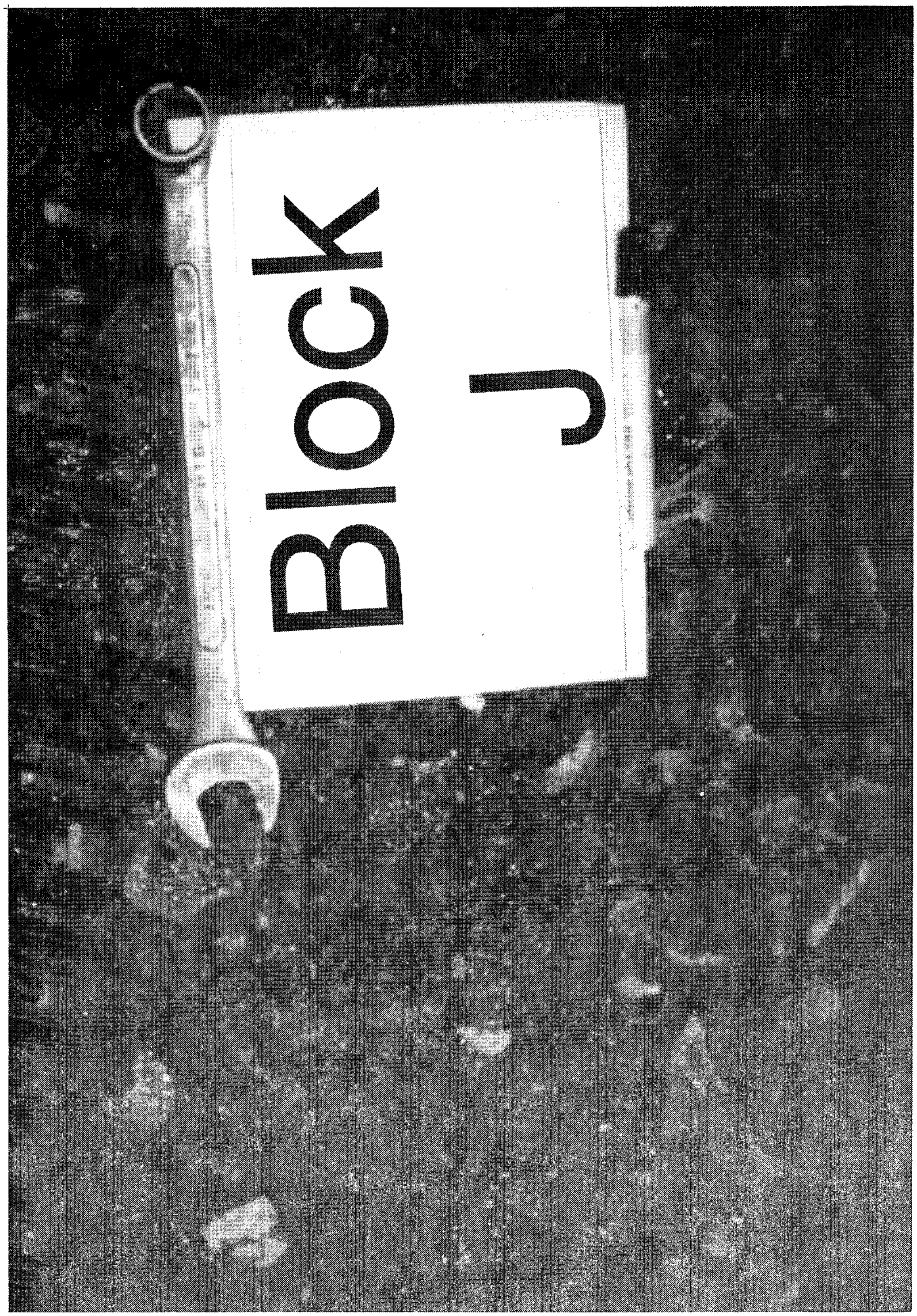

Figure A20. Close-up of joint surface of Block J, air-water cutting (extra depth), continually wet

Figure A21. Joint surface of Block K, air-water cutting (extra depth), dry

Figure A22. Close-up of joint surface of Block K, air-water cutting (extra depth), dry

Figure A23. Joint surface of Block L, air-water cutting (extra depth), dry then rewet

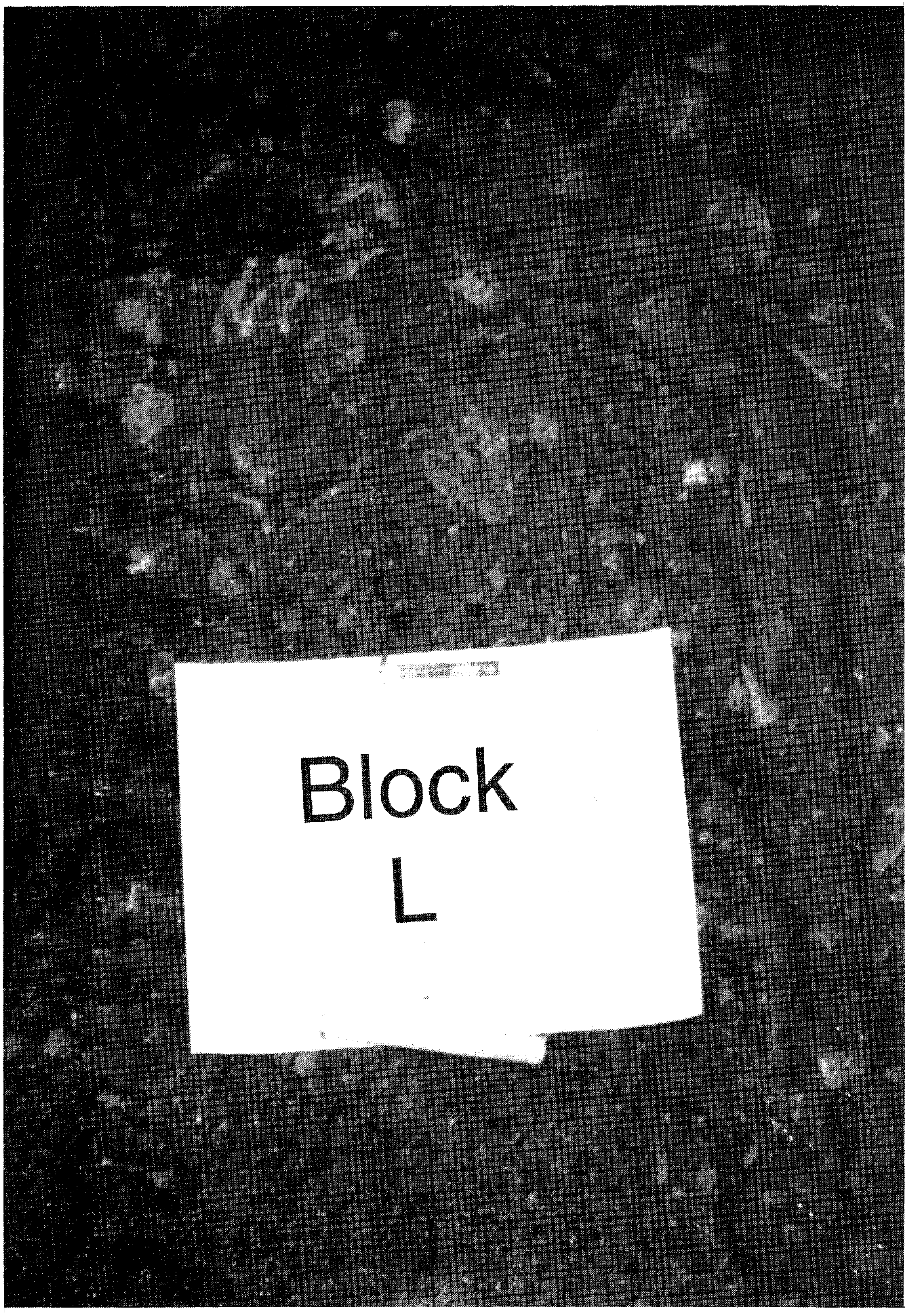

Figure 24. Close-up of joint surface of Block L, air-water cutting (extra depth), dry then rewet

Appendix B
Statistical Analysis of Tensile Strength Data

Table B1
Two-Way ANOVA for Effect of Surface Treatment and Moisture Condition on Direct-Tensile Strength of Jointed Specimens, all Data Included

Source	Sum of Squares	Degrees of Freedom	Mean Square	P
Joint treatment condition	129,251.6	3	43,083.9	0.0001
Moisture condition	23,225.1	2	11,612.5	0.0007
Joint treatment x moisture condition	33,799.7	6	5,633.2	0.0020
Error	68,483.7	50	1,369.7	
Total	254,759.7	61		

Table B2
Results of Duncan's Test on Surface-Treatment Means

Grouping	Mean	N	Condition
A	203.8 kPa	13	Air-water
A	189.1	16	HP water
B	151.9	16	Air-water +
C	86.2	17	None

Table B3
Results of Duncan's Test on Moisture-Condition Means

Grouping	Mean	N	Condition
A	176.7 kPa	24	Dry
B	150.6	17	Dry-rewet
B	131.4	21	Wet

Table B4
One-way ANOVA of Effect of Moisture Condition on Direct Tensile Strength of Blocks that Received No Surface Treatment

Source	Sum of Squares	Degrees of Freedom	Mean Square	P
Moisture condition	18,039.8	2	9,019.9	0.0005
Error	9,086.7	14	649.0	
Total	27,126.5	16		

Table B5
Results of Duncan's Test on Moisture-Condition Means

Grouping	Mean	N	Condition
A	118.3 kPa	6	Dry
A	99.0	5	Dry-rewet
B	43.3	6	Wet

Table B6
One-Way ANOVA of Effect of Moisture Condition on Direct Tensile Strength of Blocks that were Treated by High-Pressure Water

Source	Sum of Squares	Degrees of Freedom	Mean Square	P
Moisture condition	15,315.1	2	7,657.6	0.0640
Error	29,095.8	13	2,238.1	
Total	44,410.9	15		

Table B7
Results of Duncan's Test on Moisture-Condition Means

Grouping	Mean	N	Condition
A	222.5 kPa	4	Dry-rewet
A, B	205.8	6	Dry
B	150.0	6	Wet

Table B8
One-Way ANOVA of Effect of Moisture Condition on Direct Tensile Strength of Blocks that were Treated by Air-Water Cutting

Source	Sum of Squares	Degrees of Freedom	Mean Square	P
Moisture condition	11,989.4	2	5,994.7	0.0714
Error	17,237.5	10	1,723.8	
Total	29,226.9	12		

Table B9
Results of Duncan's Test on Moisture-Condition Means

Grouping	Mean	N	Condition
A	234.2 kPa	6	Dry
A, B	191.7	3	Dry-rewet
B	165.0	4	Wet

Table B10
One-Way ANOVA of Effect of Moisture Condition on Direct Tensile Strength of Blocks that were Treated by Air-Water Cutting to Extra Depth

Source	Sum of Squares	Degrees of Freedom	Mean Square	P
Moisture condition	11,680.4	2	5,840.2	0.0157
Error	13,063.3	13	1,004.9	
Total	24,743.8	15		

Table B11
Results of Duncan's Test on Moisture-Condition Means

Grouping	Mean	N	Condition
A	222.5 kPa	5	Wet
A, B	205.8	6	Dry
B	150.0	5	Dry-rewet

Appendix C
Failure Envelopes from Shear Tests[1]

[1] To convert from non-SI unit, degree, to the SI unit, radian, multiply degree by 0.01745329.

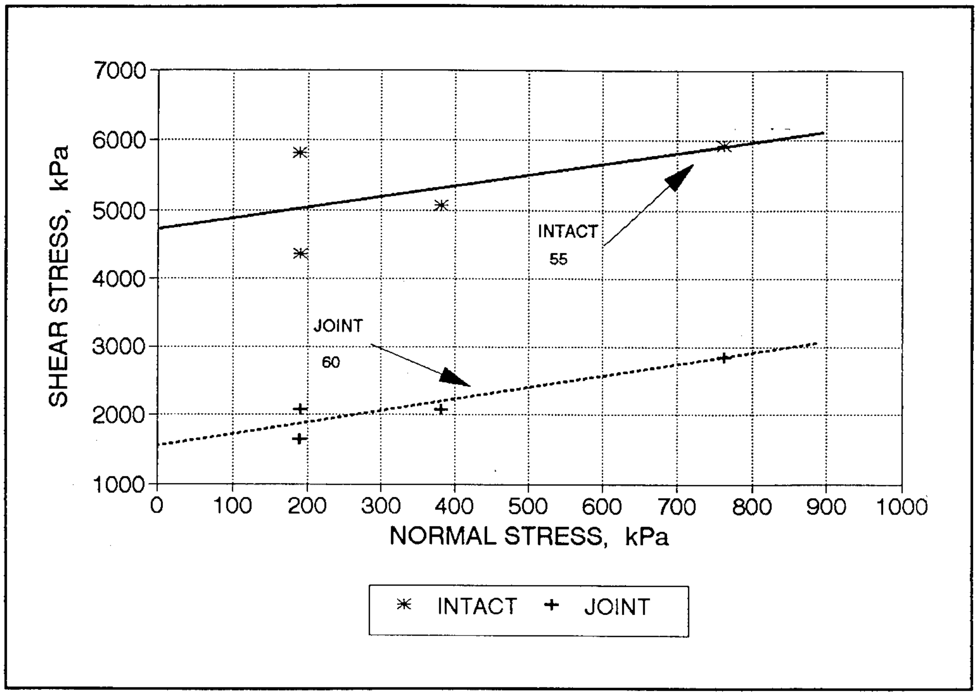

Figure C1. Maximum shear stress failure envelope, Block A, no joint cleanup, continually wet

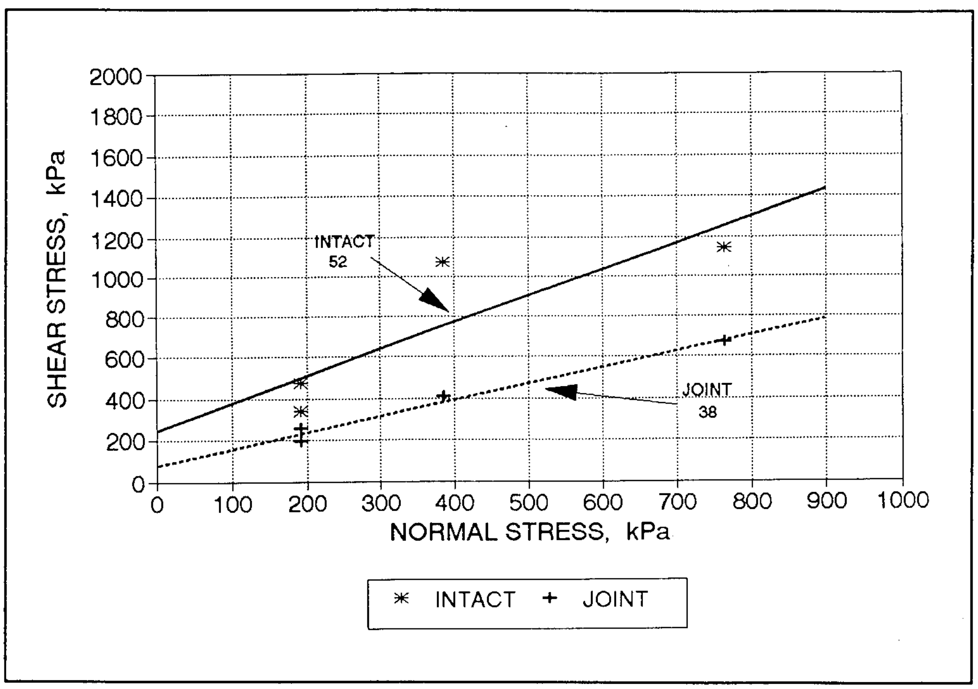

Figure C2. Residual shear stress failure envelope, Block A, no joint cleanup, continually wet

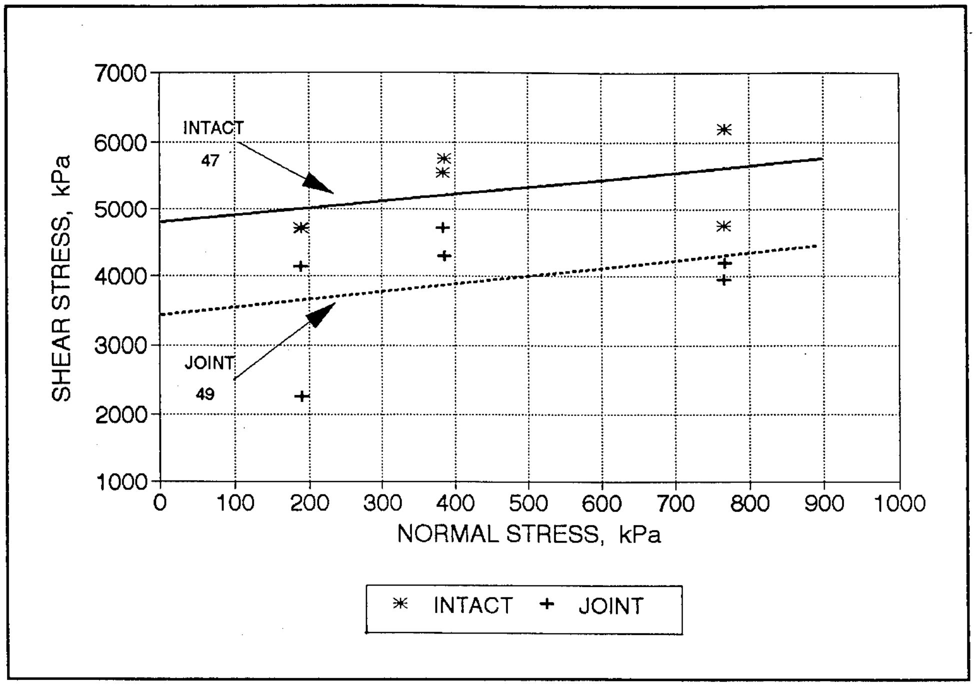

Figure C3. Maximum shear stress failure envelope, Block B, no joint cleanup, dry

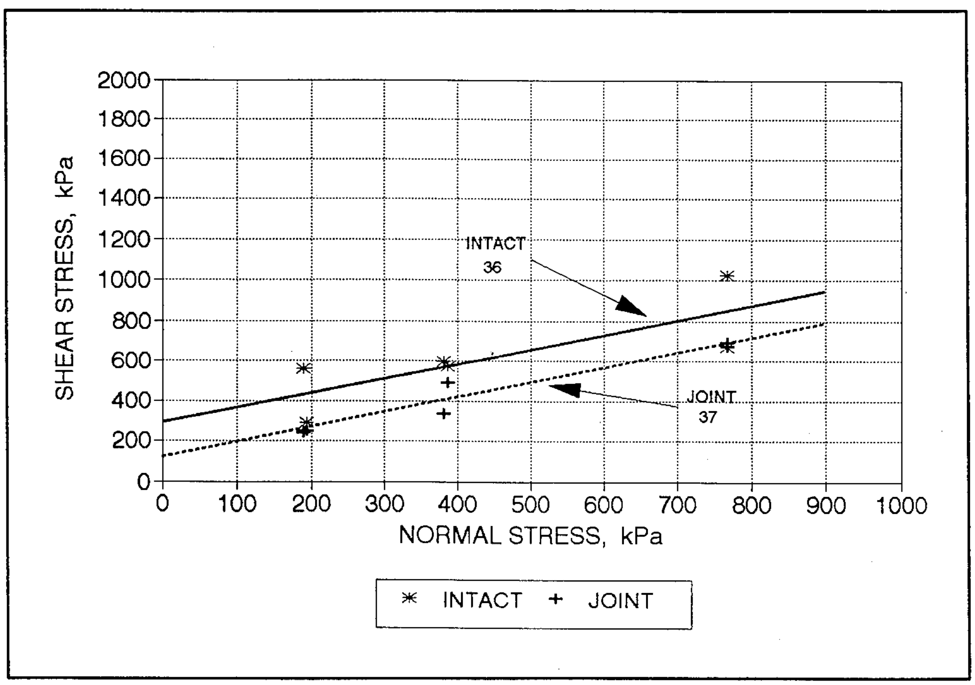

Figure C4. Residual shear stress failure envelope, Block B, no joint cleanup, dry

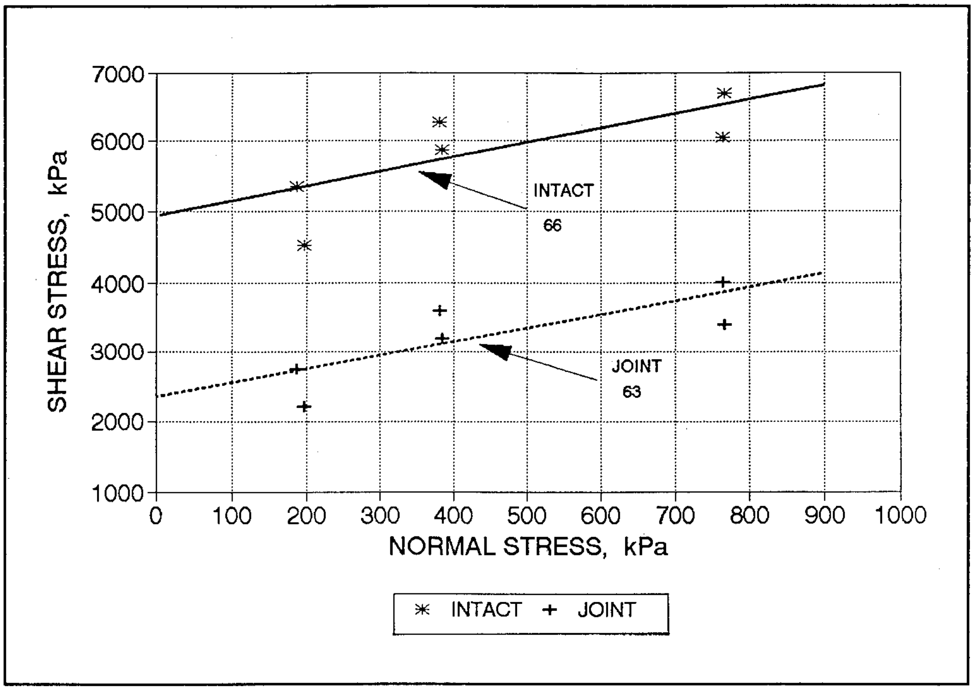

Figure C5. Maximum shear stress failure envelope, Block C, no joint cleanup, dry then rewet

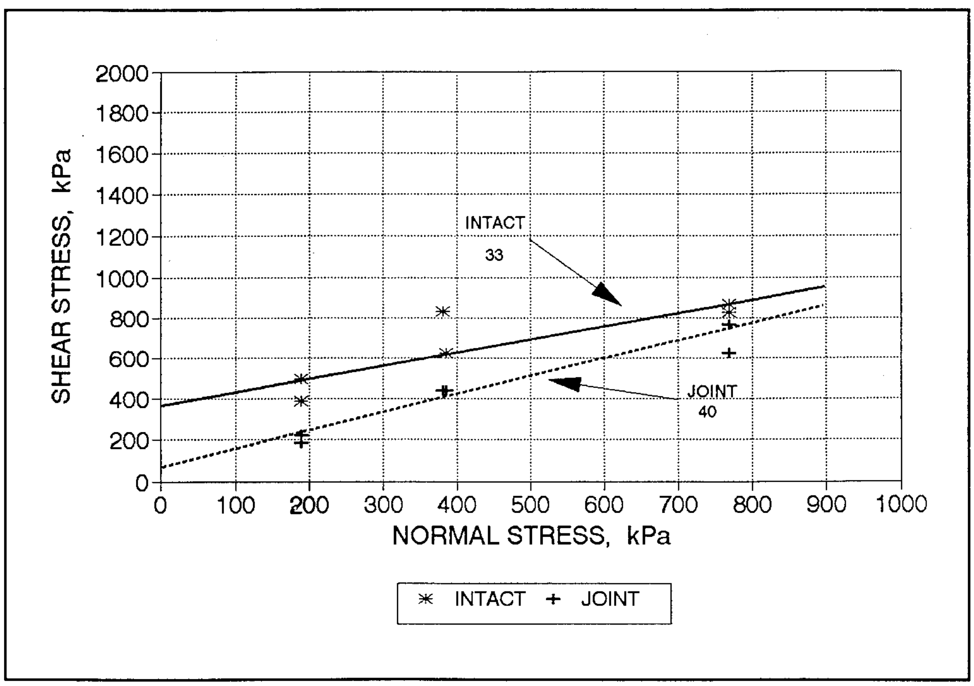

Figure C6. Residual shear stress failure envelope, Block C, no joint cleanup, dry then rewet

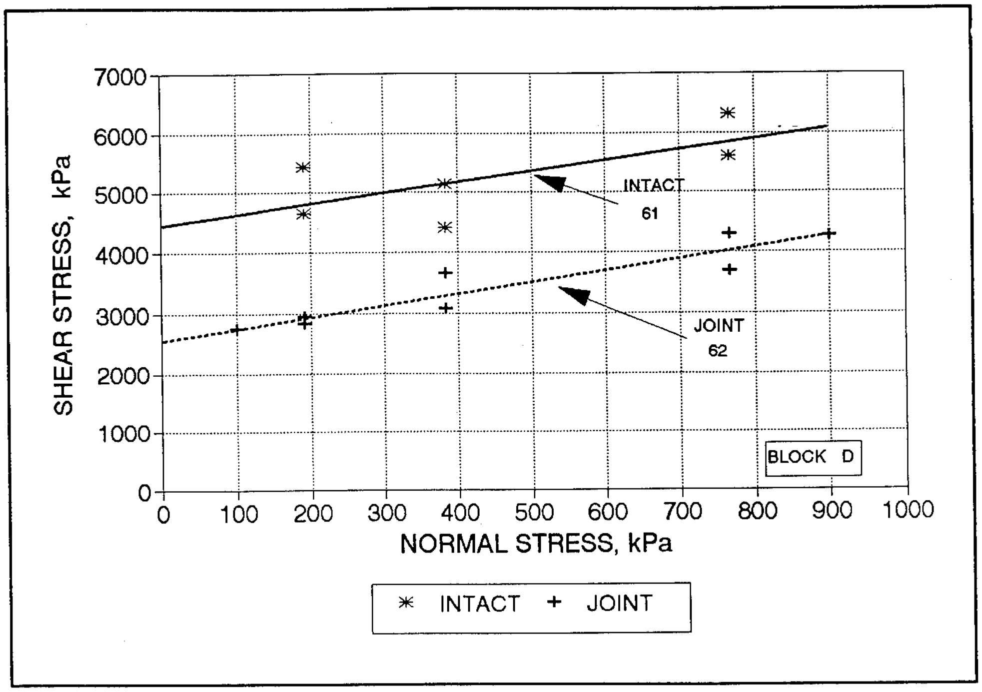

Figure C7. Maximum shear stress failure envelope, Block D, high-pressure water jet, continually wet

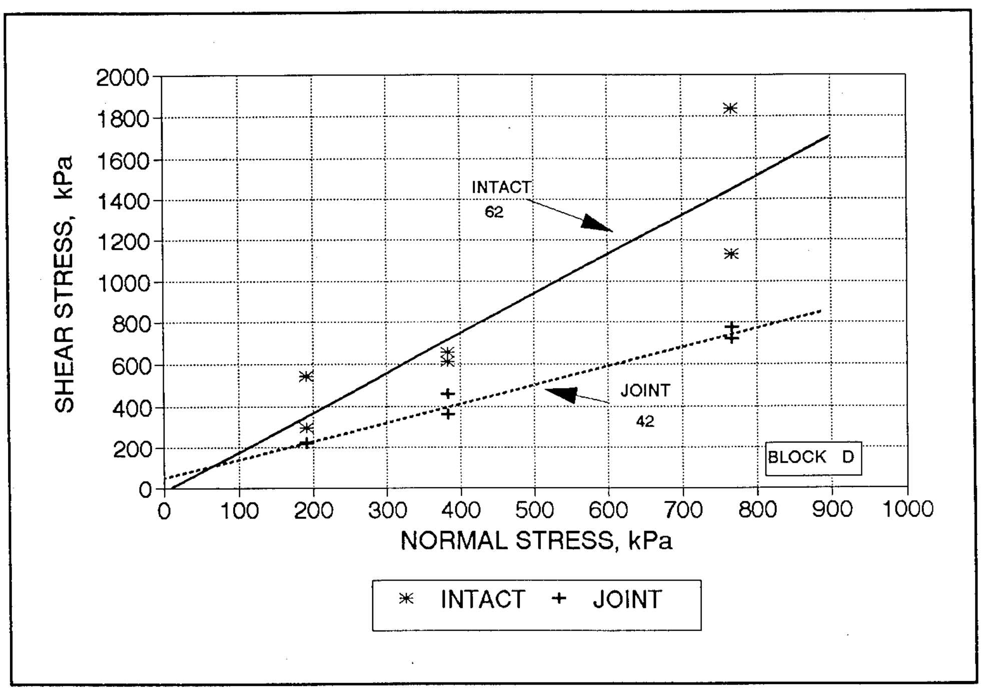

Figure C8. Residual shear stress failure envelope, Block D, high-pressure water jet, continually wet

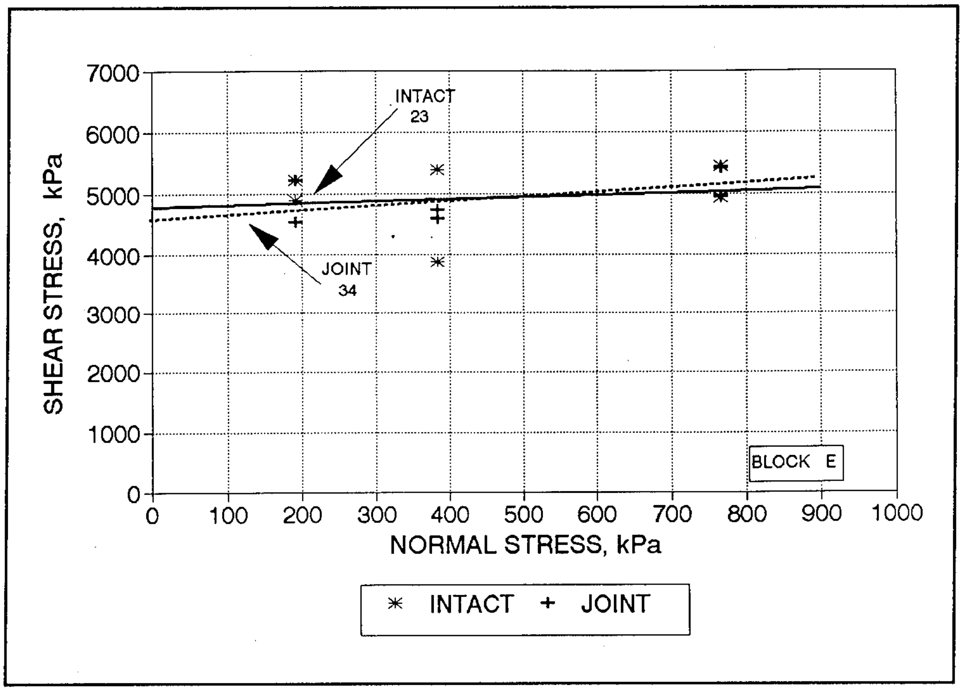

Figure C9. Maximum shear stress failure envelope, Block E, high-pressure water jet, dry

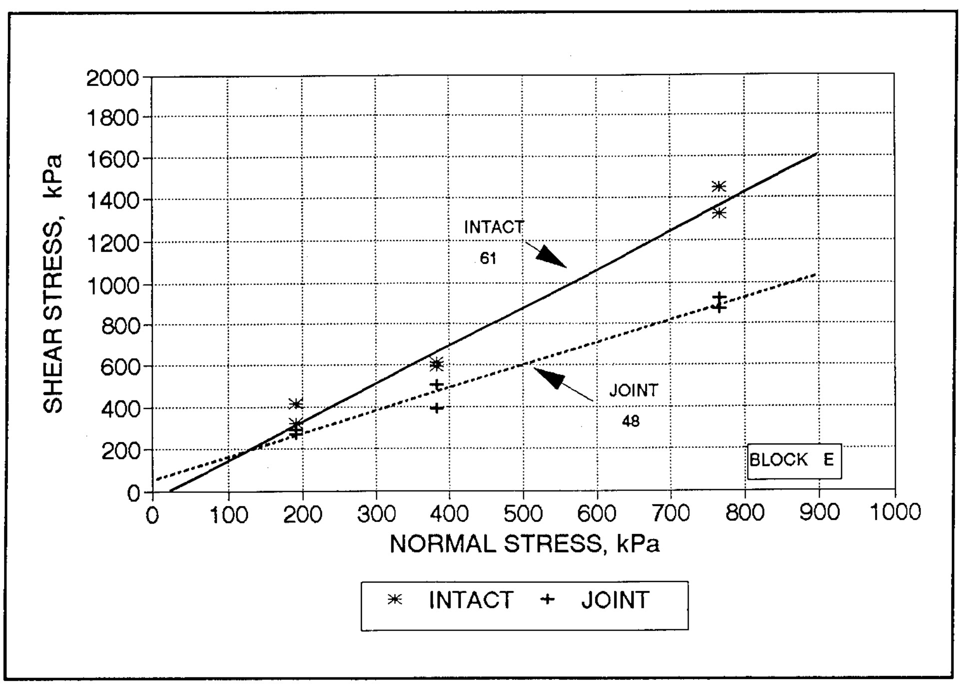

Figure C10. Residual shear stress failure envelope, Block E, high-pressure water jet, continually dry

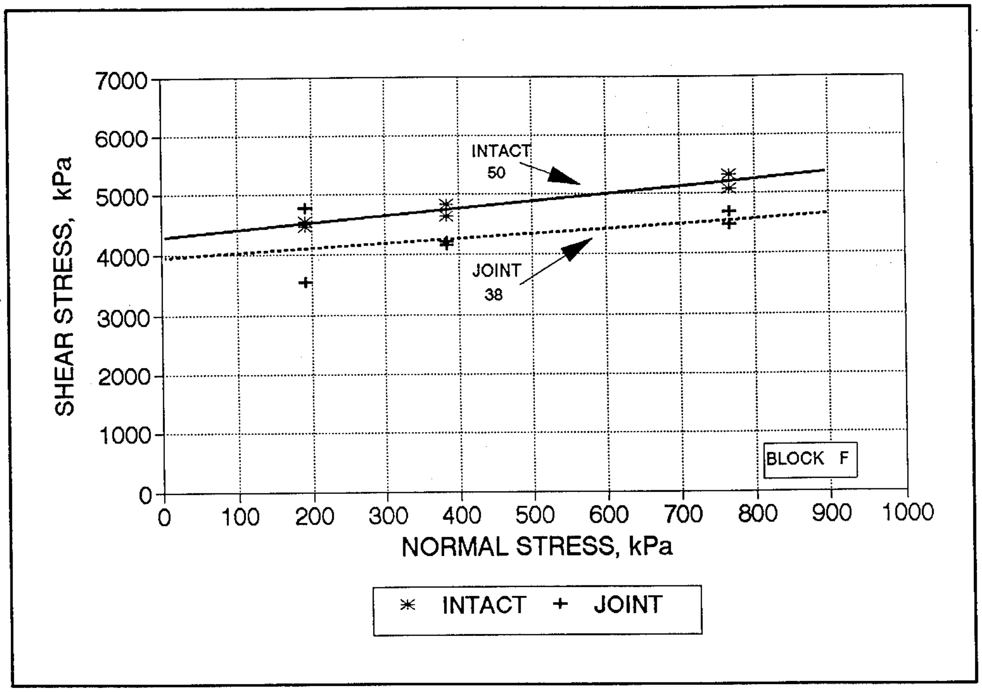

Figure C11. Maximum shear stress failure envelope, Block F, high-pressure water jet, dry then rewet

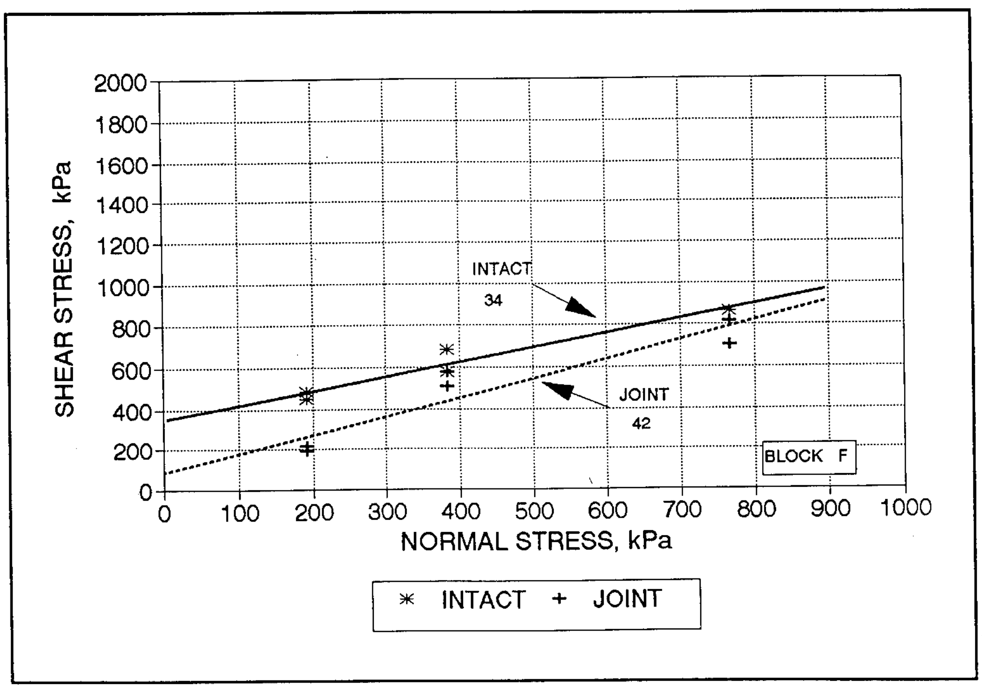

Figure C12. Residual shear stress failure envelope, Block F, high-pressure water jet, dry then rewet

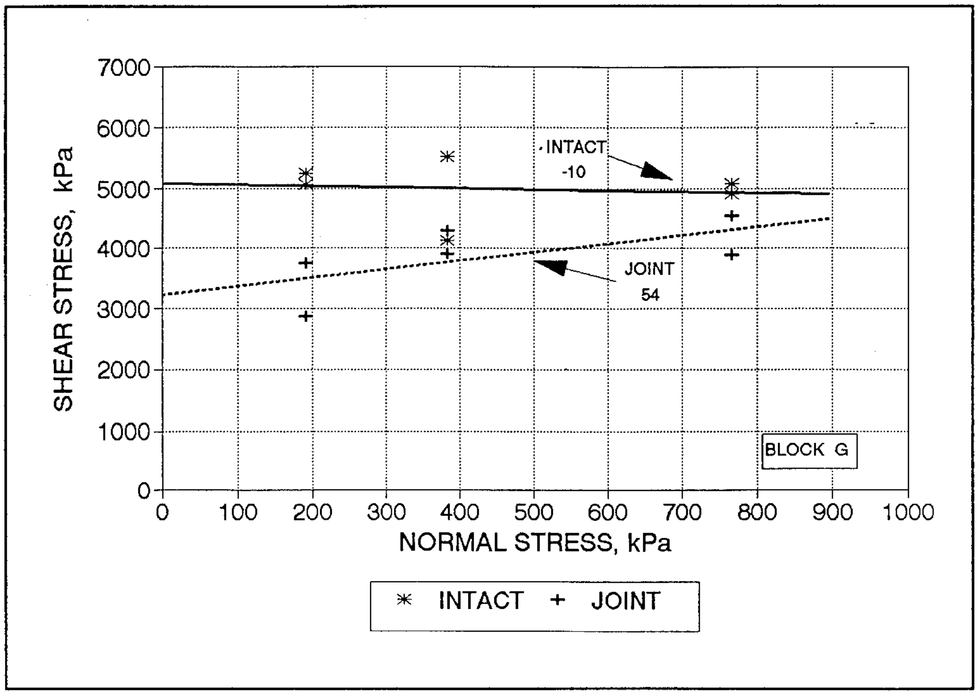

Figure C13. Maximum shear stress failure envelope, Block G, air-water cutting, wet continually

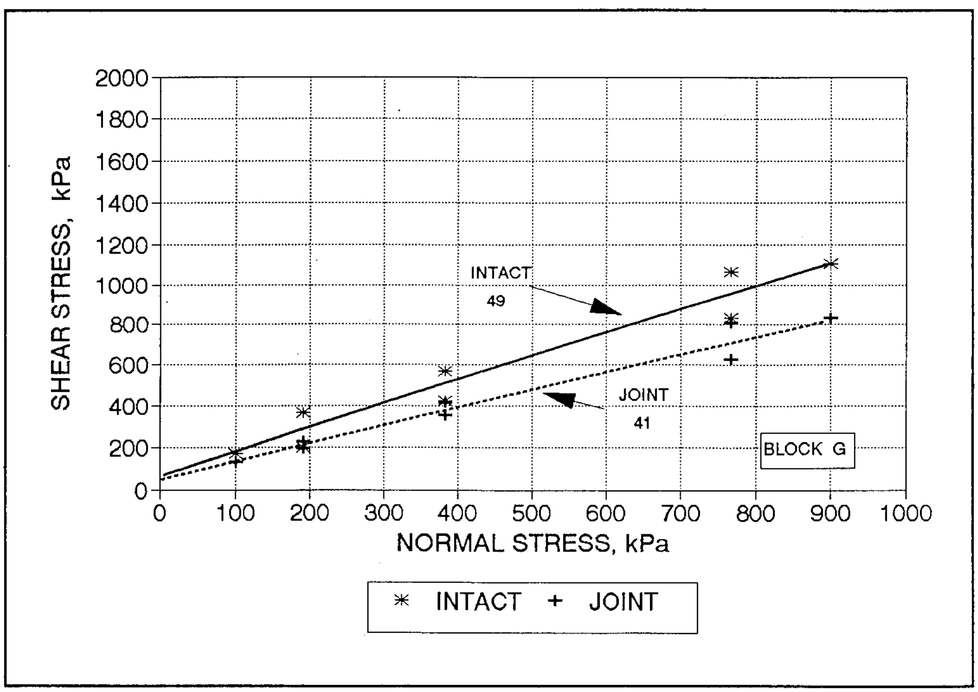

Figure C14. Residual shear stress failure envelope, Block G, air-water cutting, wet continually

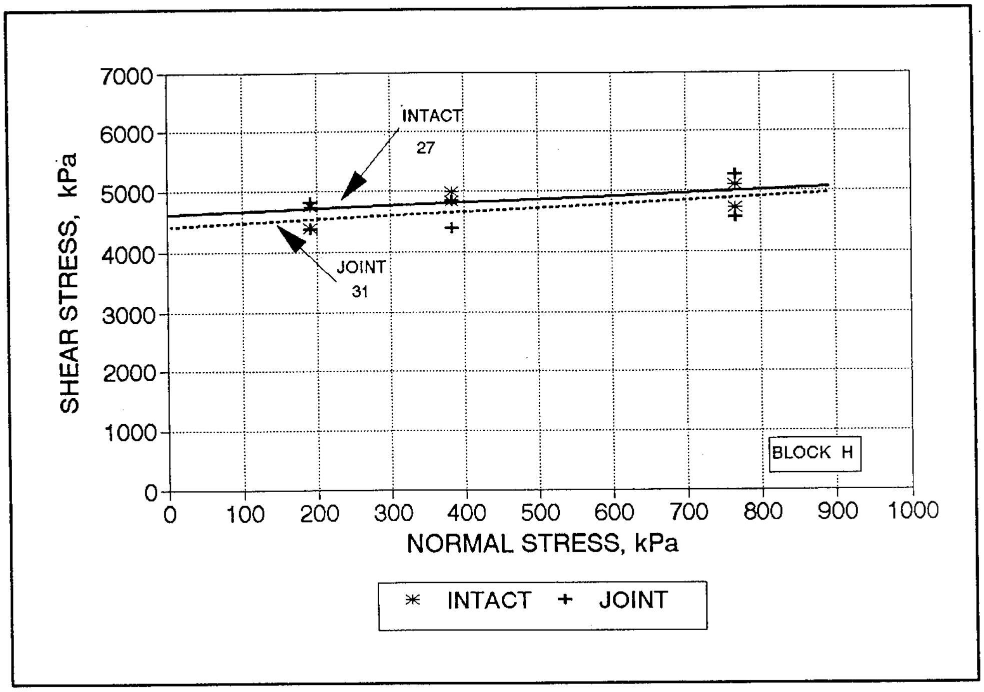

Figure C15. Maximum shear stress failure envelope, Block H, air-water cutting, dry

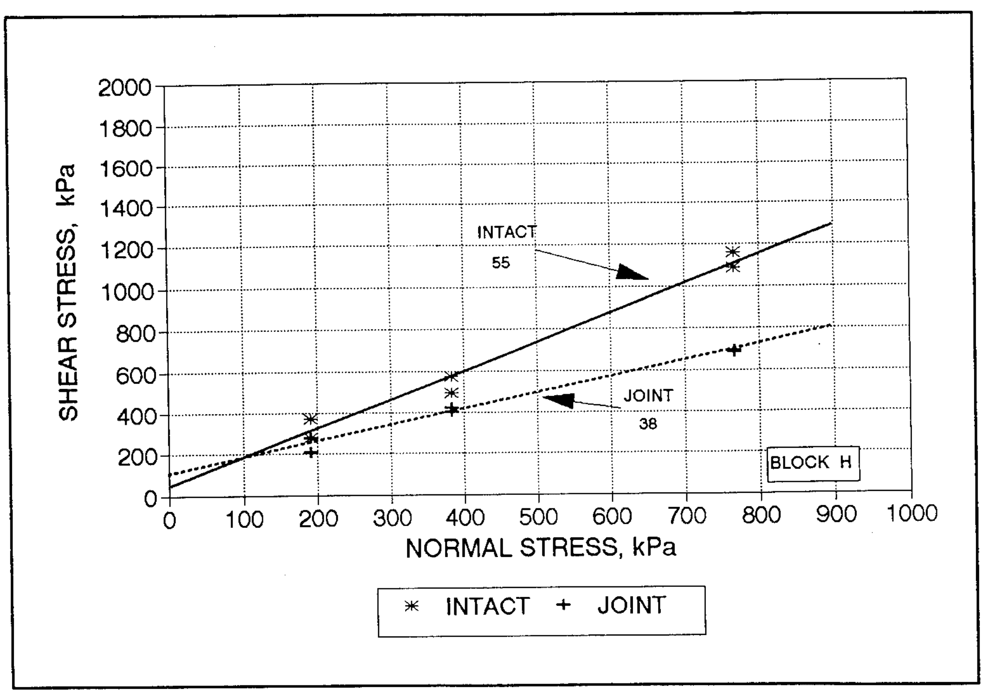

Figure C16. Residual shear stress failure envelope, Block H, air-water cutting, dry

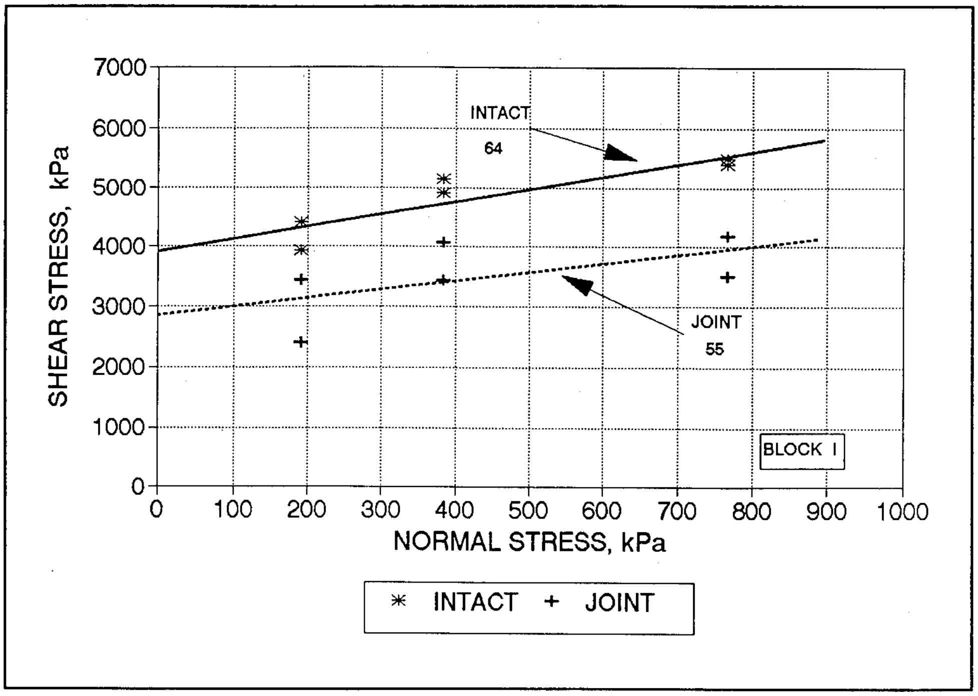

Figure C17. Maximum shear stress failure envelope, Block I, air-water cutting, dry then rewet

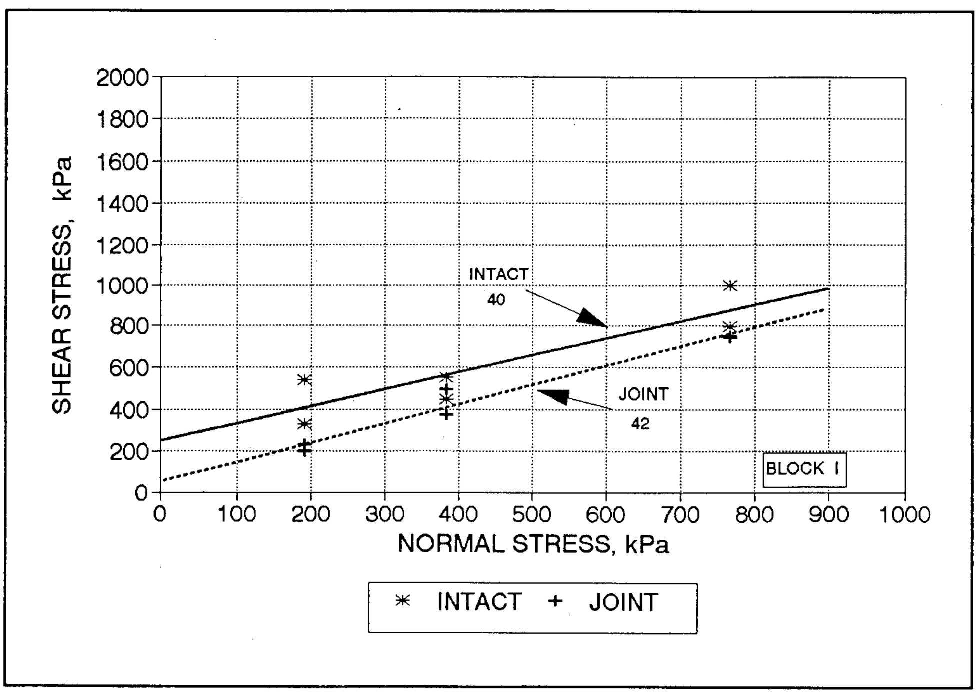

Figure C18. Residual shear stress failure envelope, Block I, air-water cutting, dry then rewet

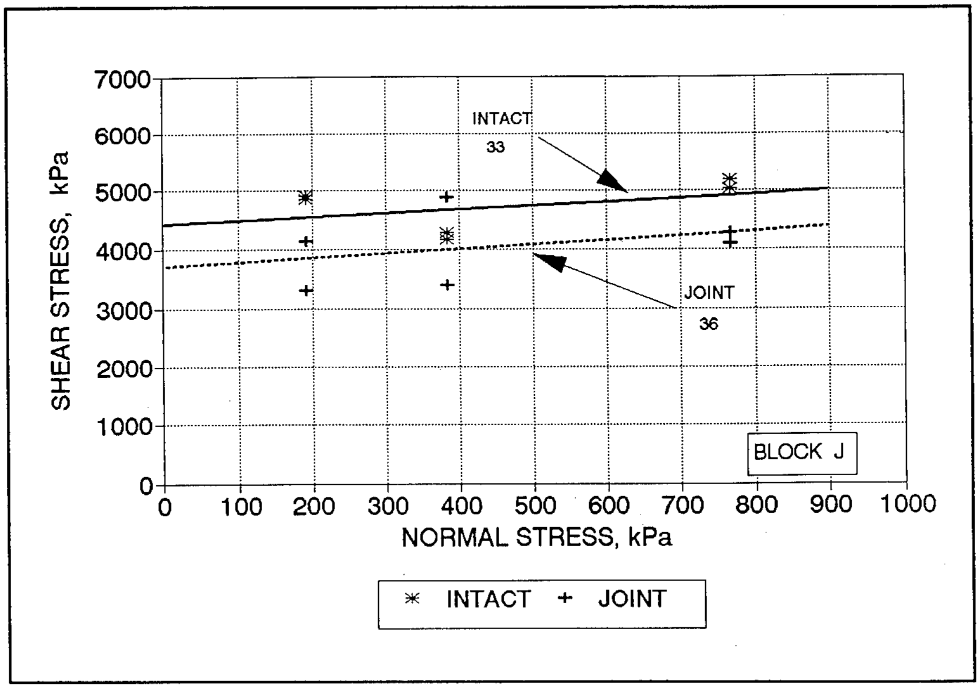

Figure C19. Maximum shear stress failure envelope, Block J, air-water cutting (extra depth), continually wet

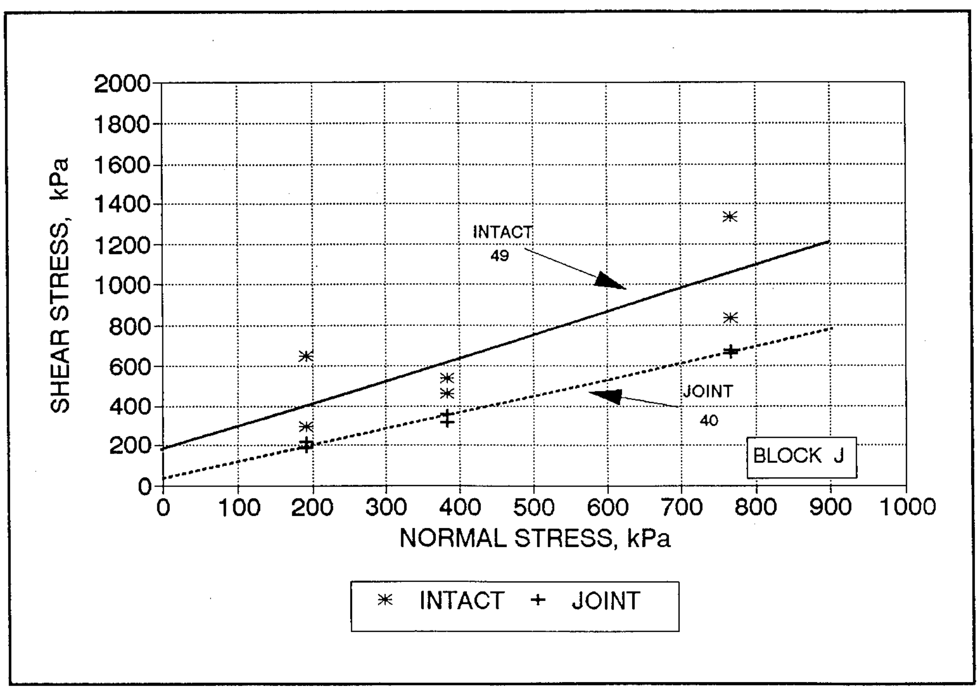

Figure C20. Residual shear stress failure envelope, Block J, air-water cutting (extra depth), continually wet

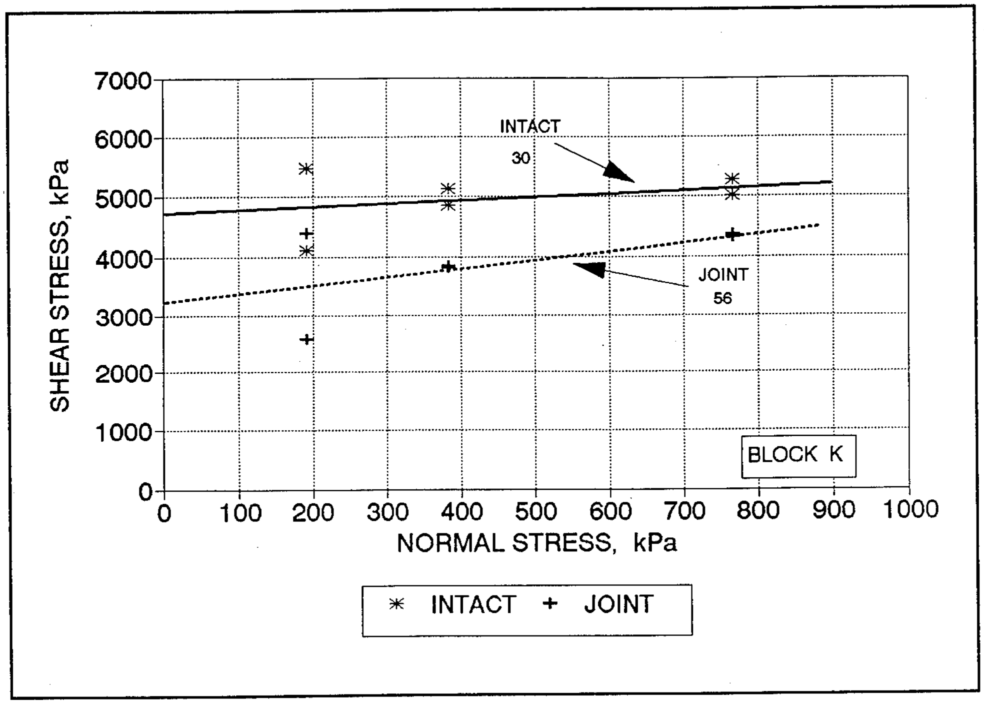

Figure C21. Maximum shear stress failure envelope, Block K, air-water cutting (extra depth), dry

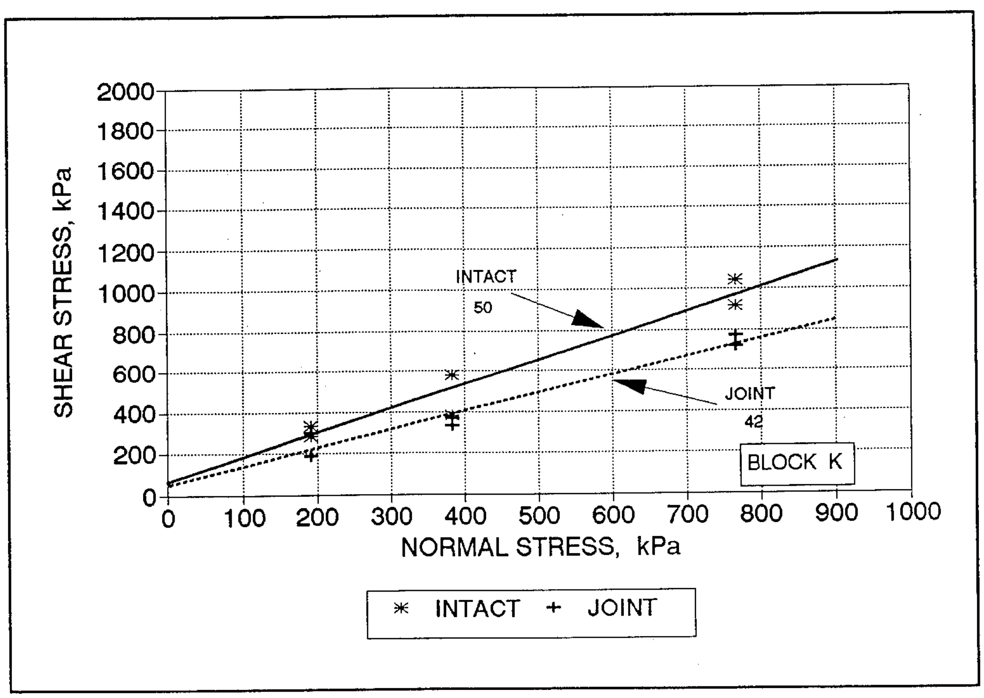

Figure C22. Residual shear stress failure envelope, Block K, air-water cutter (extra depth), dry

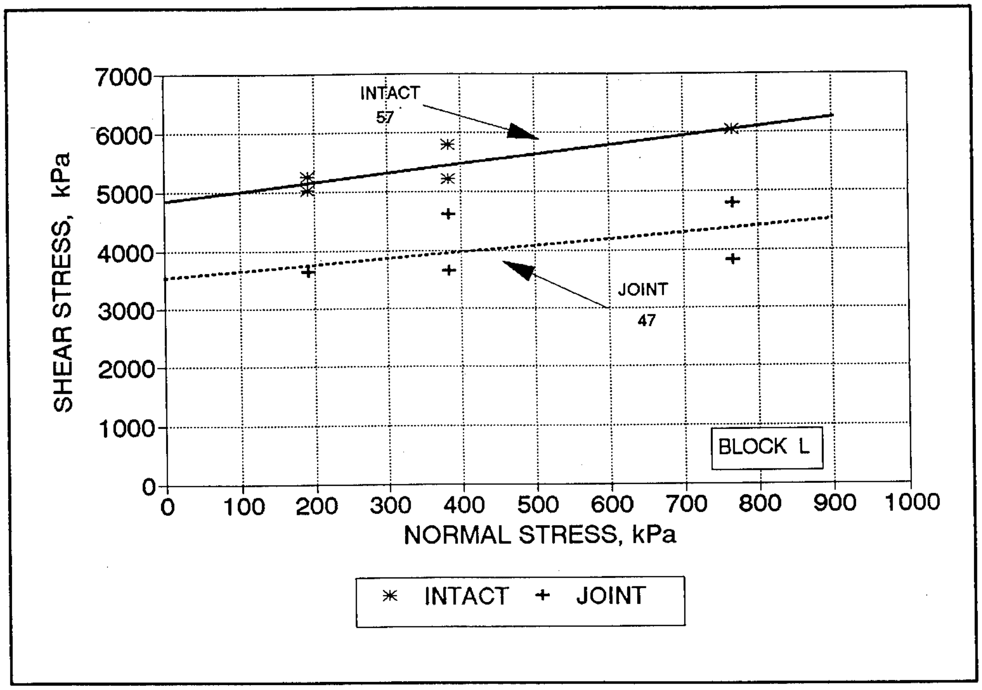

Figure C23. Maximum shear stress failure envelope, Block L, air-water cutting (extra depth), dry then rewet

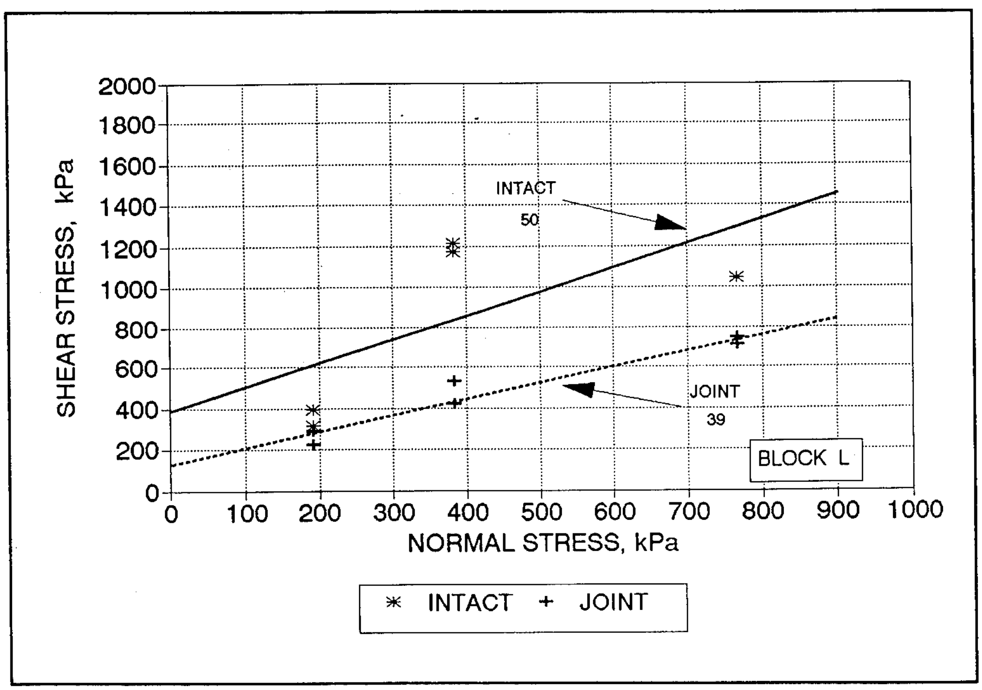

Figure C24. Residual shear stress failure envelope, Block L, air-water cutting (extra depth), dry then rewet

Appendix D
Statistical Analysis of Shear Data

Table D1
Two-way ANOVA for Effect of Surface Treatment and Moisture Condition on ϕ Angles Associated with Maximum-Shear Tests (There was no replication in this analysis, therefore, no interactive effects could be calculated.)

Source	Sum of Squares	Degrees of Freedom	Mean Square	P
Joint treatment condition	0.0906	3	0.0302	0.6220
Moisture condition	0.0659	2	0.0330	0.5386
Error	0.2878	6	0.0480	
Total	0.4445	11		

Table D2
Two-way ANOVA for Effect of Surface Treatment and Moisture Condition on ϕ Angles Associated with Residual-Shear Tests (There was no replication in this analysis, therefore, no interactive effects could be calculated.)

Source	Sum of Squares	Degrees of Freedom	Mean Square	P
Joint treatment condition	0.0185	3	0.0062	0.0623
Moisture condition	0.00066	2	0.0033	0.8028
Error	0.0087	6	0.0014	
Total	0.0279	11		

Appendix E
Statistical Analysis of Permeability Data

Table E1
Two-way ANOVA for Effect of Surface Treatment and Moisture Condition on Permeability of Jointed Specimens, all Data Included

Source	Sum of Squares	Degrees of Freedom	Mean Square	P
Joint treatment condition	1,795.5	3	598.5	0.0001
Moisture condition	677.9	2	339.0	0.0011
Joint treatment x moisture condition	732.9	6	122.1	0.0195
Error	2,653.9	60	44.2	
Total	5,860.2	71		

Table E2
Results of Duncan's Test on Surface-Treatment Means

Grouping	Mean	N	Condition
A	16.6 m^2/m ($\times 10^{-18}$)	18	Air-water +
B	10.8	18	HP water
B	10.4	18	None
C	2.5	18	Air-water

Table E3
Results of Duncan's Test on Moisture-Condition Means

Grouping	Mean	N	Condition
A	14.2 m^2/m ($\times 10^{-18}$)	24	Dry-rewet
B	9.2	24	Wet
B	6.8	24	Dry

Table E4
One-way ANOVA of Effect of Moisture Condition on Permeability of Joints in Blocks that Received No Surface Treatment

Source	Sum of Squares	Degrees of Freedom	Mean Square	P
Moisture condition	278.2	2	139.1	0.2422
Error	1,336.9	15	89.1	
Total	1,615.1	17		

Table E5
Results of Duncan's Test on Moisture-Condition Means

Grouping	Mean	N	Condition
A	13.4 m^2/m ($\times 10^{-18}$)	6	Wet
A	12.9	6	Dry-rewet
A	4.8	6	Dry

Table E6
One-way ANOVA of Effect of Moisture Condition on Permeability of Joints in Blocks that were Treated by High-Pressure Water

Source	Sum of Squares	Degrees of Freedom	Mean Square	P
Moisture condition	50.9	2	25.5	0.5378
Error	590.8	15	39.4	
Total	641.8	17		

Table E7
Results of Duncan's Test on Moisture-Condition Means

Grouping	Mean	N	Condition
A	12.6 m^2/m ($\times 10^{-18}$)	6	Wet
A	11.2	6	Dry-rewet
A	8.5	6	Dry

Table E8
One-way ANOVA of Effect of Moisture Condition on Permeability of Joints in Blocks that were Treated by Air-Water Cutting

Source	Sum of Squares	Degrees of Freedom	Mean Square	P
Moisture condition	95.5	2	48.3	0.0001
Error	24.1	15	1.7	
Total	122.6	17		

Table E9
Results of Duncan's Test on Moisture-Condition Means

Grouping	Mean	N	Condition
A	5.7 m^2/m ($\times 10^{-18}$)	6	Dry-rewet
B	1.7	3	Dry
B	0.2	4	Wet

Table E10
One-way ANOVA of Effect of Moisture Condition on Permeability of Joints of Blocks that were Treated by High-Pressure Water, Cutting to Extra Depth

Source	Sum of Squares	Degrees of Freedom	Mean Square	P
Moisture condition	985.1	2	492.6	0.0014
Error	700.0	15	46.7	
Total	1,685.1	17		

Table E11
Results of Duncan's Test on Moisture-Condition Means

Grouping	Mean	N	Condition
A	27.0 m^2/m ($\times 10^{-18}$)	6	Dry-rewet
B	12.3	6	Dry
B	10.4	6	Wet

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13. ABSTRACT *(Maximum 200 words)*

This report presents the results of a research program examining the effects of different methods of preparing horizontal construction joints in mass concrete construction. The purpose of the research program was to confirm existing guidance or, if necessary, update it.

The joint cleaning procedures employed were (a) none, (b) high-pressure water cutting, (c) air-water cutting, and (d) air-water cutting to greater depth. The joint moisture conditions at the time of concrete placement were (a) continuously moist, (b) dry, and (c) dry and then remoistened. Jointed specimens were tested for direct tensile strength, shear strength, and permeability.

The results indicated that good bond strengths are realized when horizontal construction joints are cleaned by high-pressure water cutting or by air-water cutting, and that undercutting coarse aggregate particles does not improve the strength of the joint. The results also indicated that better bond strengths are realized when the joint surface is allowed to dry approximately 24 hr immediately prior to placement of the next lift of concrete.

Recommendations are made to consider revising current guidance to permit placement of concrete on a dry surface. No revisions to current guidance are recommended concerning joint cleaning procedures.

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